Utilizing Direct Numerical Simulations Of Transition and Turbulence in Design Optimization

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MOTIVATION

DO WE NEED DNS IN DESIGN OPTIMIZATION?

Designing Rocket Engine Components for Sustainable Space Exploration…An Introduction

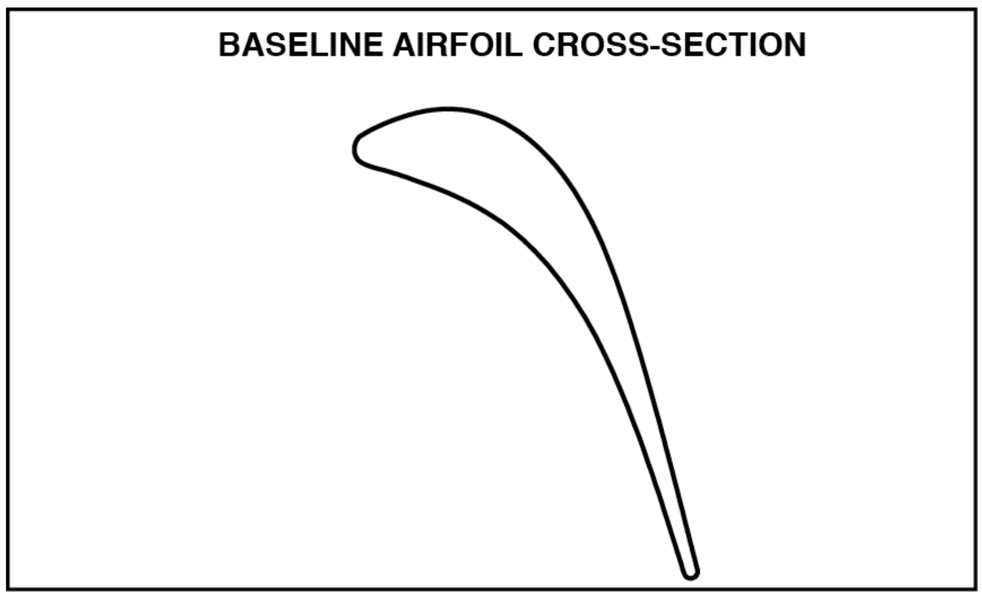
- **Component requirements**
    - **Light, compact and possesses necessary strength**
    - **Robust performance**
        - **Performance insensitivity to**
            - **Manufacturing tolerances and normal wear and tear**
            - **Changing operating conditions**
    - **Reliable performance**
        - **Constraint satisfaction in the presence of variability**
- **Benefits**
    - **Increased safety and reliability, reduced lifetime costs and system downtime**

Design Challenges

- System redundancy is not always a solution
    - Weight/cost penalty
    - Design susceptibility to a set of operating/external characteristics…a duplicate may not be the answer
- Repair/replacement may not be practical in space
- High-dimensional search spaces
- Multiple conflicting objectives and numerous constraints
- Multidisciplinary
- Complex physics$\Rightarrow$compute intensive simulations (3D, unsteady)
- Robustness requirement

SSME LPOTP Redesign….Background

- **Inspection of the first vane showed evidence of high cycle fatigue (HCF) in the trailing edge region near the hub and shroud**
    - **Component was replaced at carefully monitored time intervals to ensure full safety of Shuttle flights**



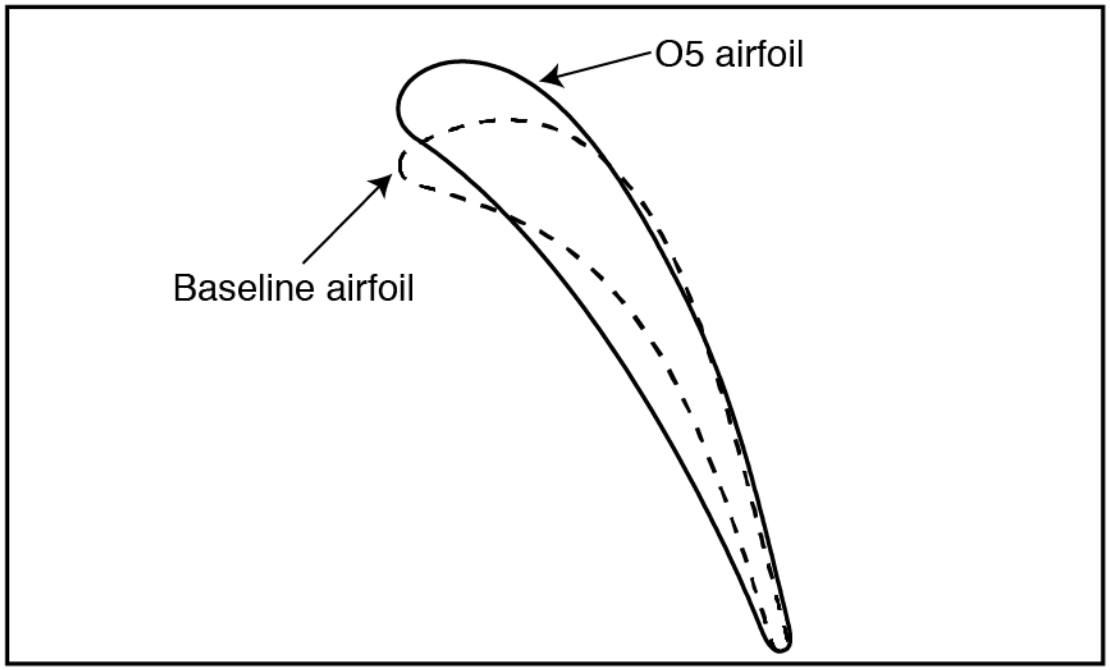
SSME LPOTP Redesign….Background Continued

- Trailing edge vortex shedding was considered the probable cause of HCF
    - Vane natural frequency (T. E. flapping mode) estimated between 24Khz and 46 Khz (uncertainty in airfoil shape and LOX effect)
    - Shedding frequency (CFD) ranges between 28Khz and 45Khz (uncertainty in airfoil shape, turbulence model etc.)
    - Overlap in frequencies combined with large amplitude shedding was considered to be the major cause of HCF (first vane, LPOTP)
- Initial “Retrofit” solution consisted of increasing the trailing edge thickness by removing small-diameter, rounded, trailing edge
    - Lowers shedding frequency as required
    - Increases natural flap mode resonance frequency
    - Creates significant new disturbance on downstream rotor

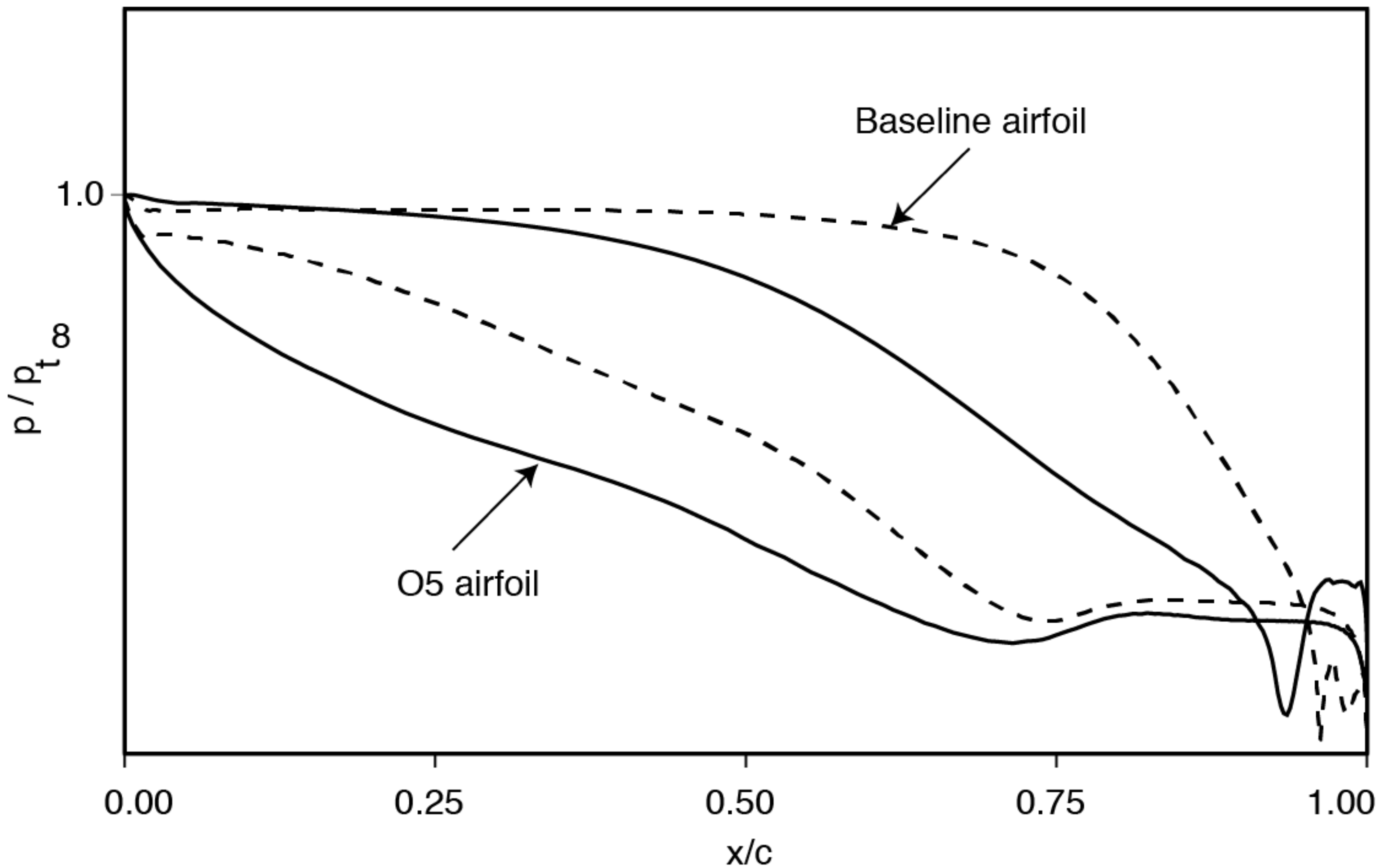
Design Requirements For First Redesign
(Collaborative Effort Between Boeing-Rocketdyne and ARC)

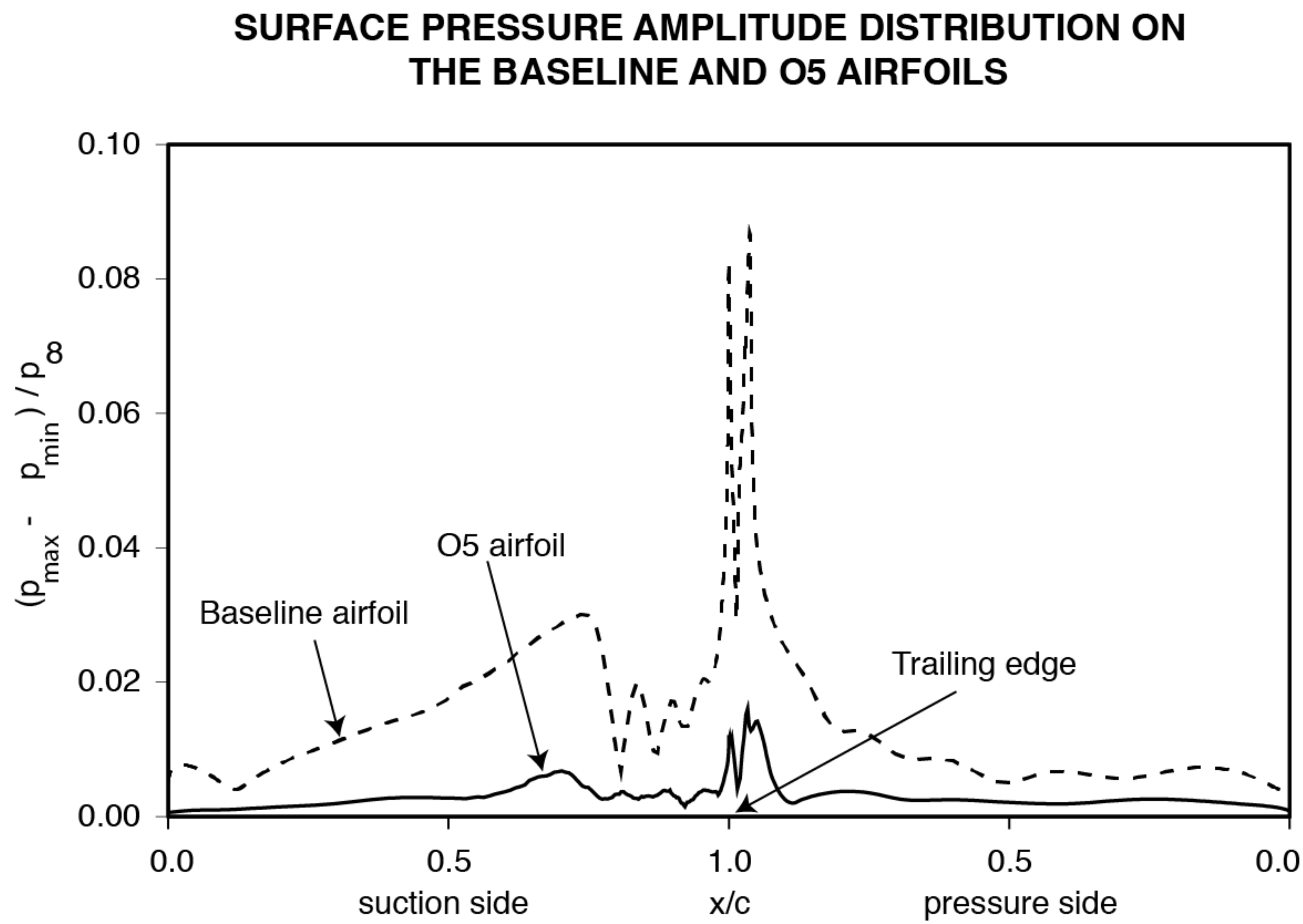
- **Increase thickness of airfoil, particularly in the trailing edge region**
    - **Strengthen airfoil**
    - **Increase vane natural frequency**
- **Decrease vortex shedding amplitude and frequency**
- **Maintain throat area and exit angle**
- **Design trailing edge which eases manufacturing process (Facilitate metal flow in casting)**
- **Reduce pressure fluctuations on downstream airfoil rows**
- **Desensitize shedding amplitude to manufacturing tolerances and normal wear and tear**
    - **Manufacturing tolerance for casting process is ±0.006 inches (Corresponding variation in baseline T. E. geometry is ~ 50%!)**

BASELINE AND OPTIMIZED (O5) AIRFOIL CROSS-SECTIONS

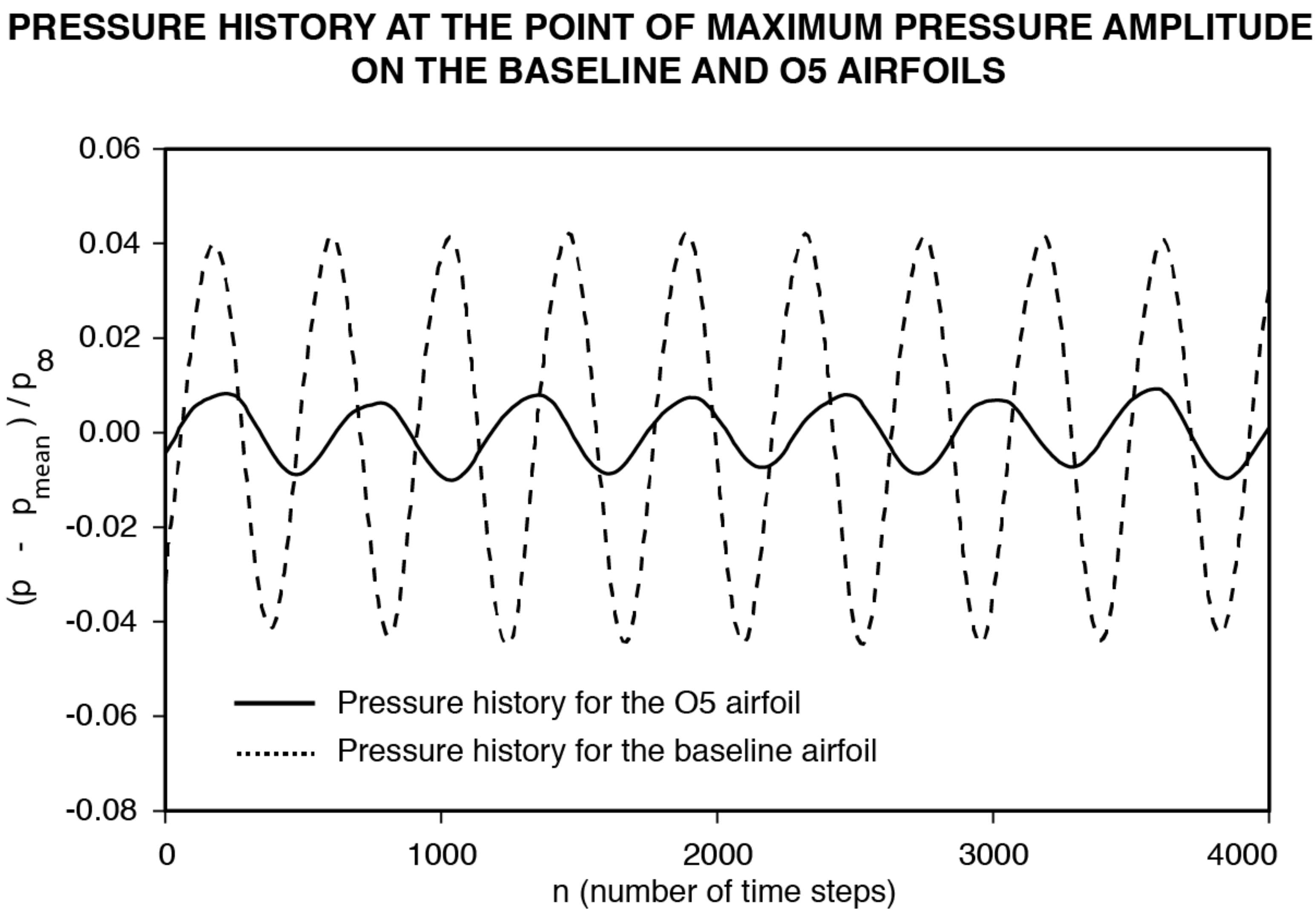


SURFACE PRESSURE DISTRIBUTION FOR THE BASELINE AND O5 AIRFOILS

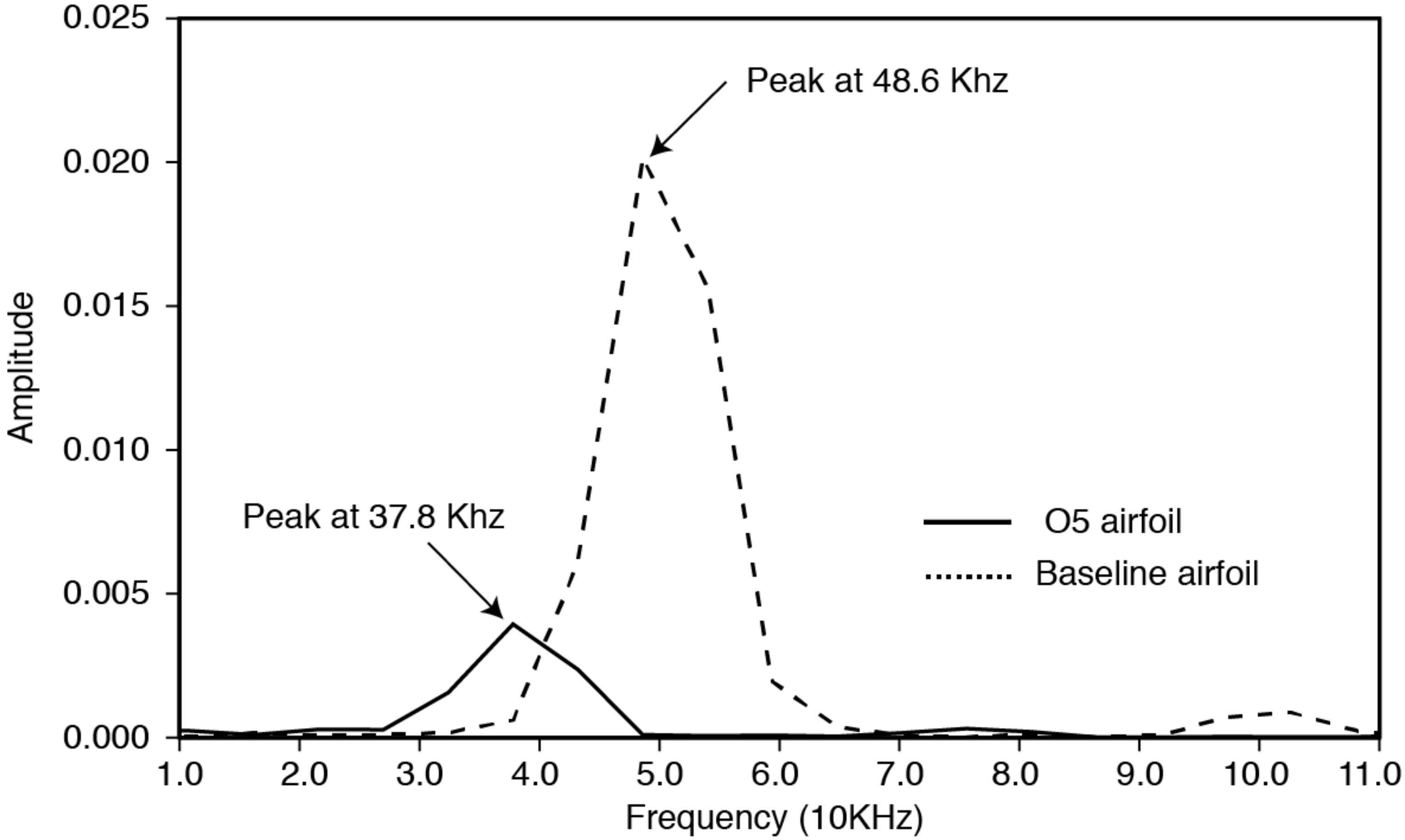




SURFACE PRESSURE AMPLITUDE DISTRIBUTION ON
THE BASELINE AND O5 AIRFOILS
(p_max - p_min) / p_8
0.10
0.08
0.06
0.04
0.02
0.00
O5 airfoil
Baseline airfoil
Trailing edge
0.0
0.5
1.0
0.5
0.0
suction side
x/c
pressure side


PRESSURE HISTORY AT THE POINT OF MAXIMUM PRESSURE AMPLITUDE
ON THE BASELINE AND O5 AIRFOILS
0.06
0.04
0.02
0.00
-0.02
-0.04
-0.06
-0.08
(p - p mean) / p 8
0
1000
2000
3000
4000
n (number of time steps)
Pressure history for the O5 airfoil
Pressure history for the baseline airfoil

SPECTRAL ANALYSIS OF PRESSURE SIGNAL AT THE POINT OF MAXIMUM AMPLITUDE ON THE BASELINE AND O5 AIRFOILS



Assessment of First Redesign
(Design by ARC, Assessment by MSFC/Rocketdyne)

- **Airfoil thickness increased significantly (stronger airfoil)**
- **Shedding and flap mode frequencies considered completely detuned**
    - **TE flap mode response peaks at about 55Khz for new airfoil (O5) (baseline airfoil peaks at 35Khz)**
- **Shedding amp. reduced by 30% - 75%, shedding freq. decreased by ~ 10Khz**
    - **Four CFD codes (different turbulence models) used in assessment**
- **Various categories of stress reduced (reduction ranges from 19% to 600%)**
    - **Overall increase in safety factor from 3.5 to 6.3**
    - **Part fitted with O5 airfoil has essentially "infinite" life**
- **Robustness of shedding amplitude to T.E. geometry variations obtained**
- **Wider trailing edge of O5 should facilitate manufacturing process**

DNS OF THE WAKE OF A FLAT PLATE WITH A CIRCULAR TRAILING EDGE

(TURBULENT BOUNDARY LAYERS)

Objectives of Wake Investigation

- Compute near wake of a flat plate via DNS (within 14 diameters, 4 cases)
  - Small θ/D, circular trailing edge, shedding is pronounced
  - Symmetric wake with turbulent boundary layers on both surfaces
- Investigate instability of detached shear layers (DSLs)
  - Explore characteristics of the detached shear layer
    - Variation in the rate of generation of shear-layer vortices
    - Destabilization of shear layer by log-layer eddies
    - Relation between shear-layer vortex generation and shedding phase
  - Establish power-law relationship between $\omega_{sl} / \omega_{st}$ and Re_θ & Re_D

Objectives of Wake Investigation…Continued

- Explore regions of localized reverse flow in the very near wake ($0.0 < x/D < 3.0$)
  - Role of rib vortices in causing this phenomenon
  - General attributes of this phenomenon
- Compute phase-averaged distributions of normal intensities & shear stress in the very near wake (random component),
  - Explore important features of these distributions
  - Compare these features with those obtained in the near wake
  - Explain these features via basic physical mechanisms (rib vortices, etc.) & distributions of corresponding production term in the budget

Objectives of Wake Investigation…Continued

- Investigate entrainment in the presence of turbulent separating boundary layers

  - Log-layer eddies convect past trailing edge largely unaltered

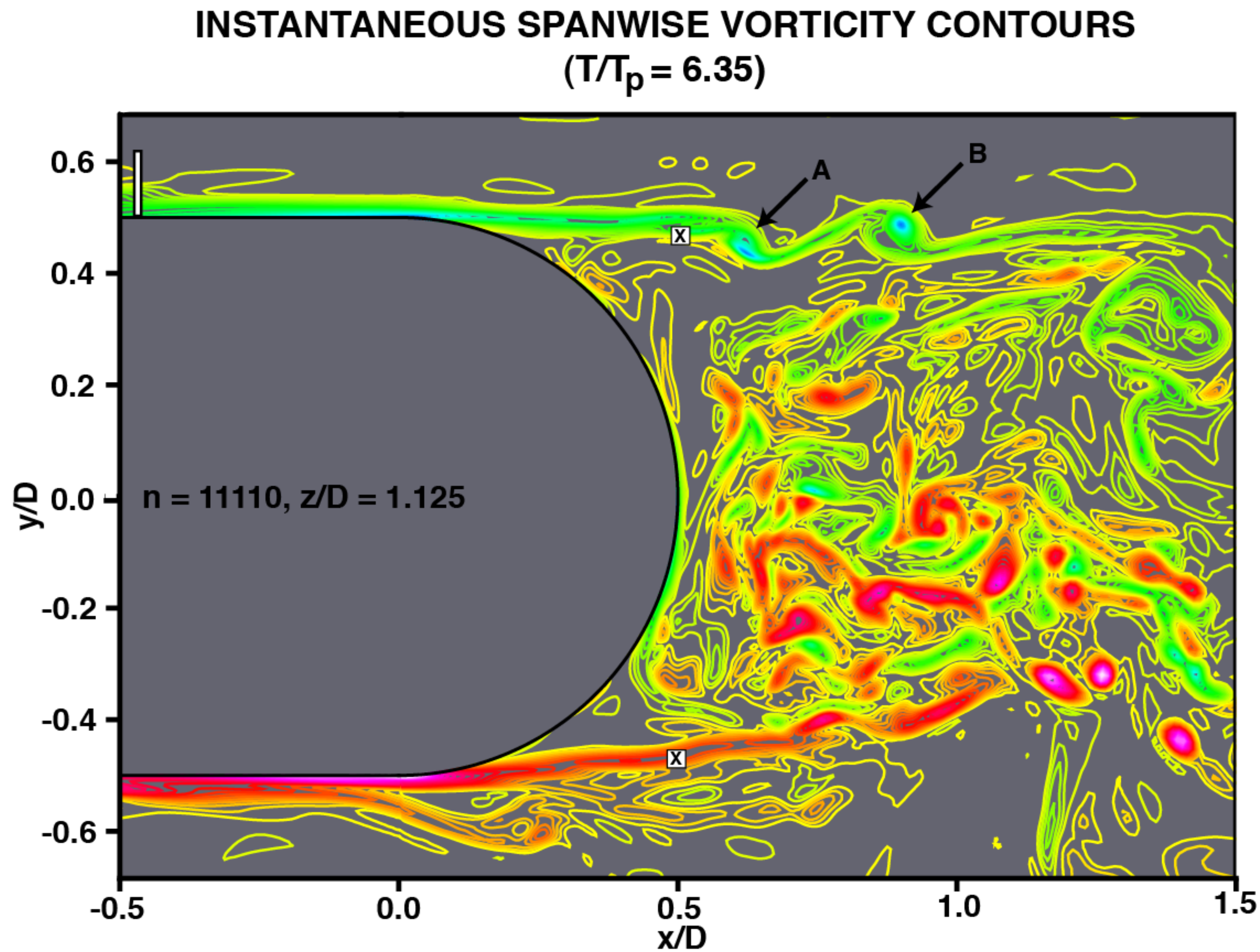
  - Assimilation of log-layer region and above by the rotational flow induced by shed vortices

  - Effect of θ/D on assimilation rate

  - Persistence of boundary layer velocity statistics in wake region

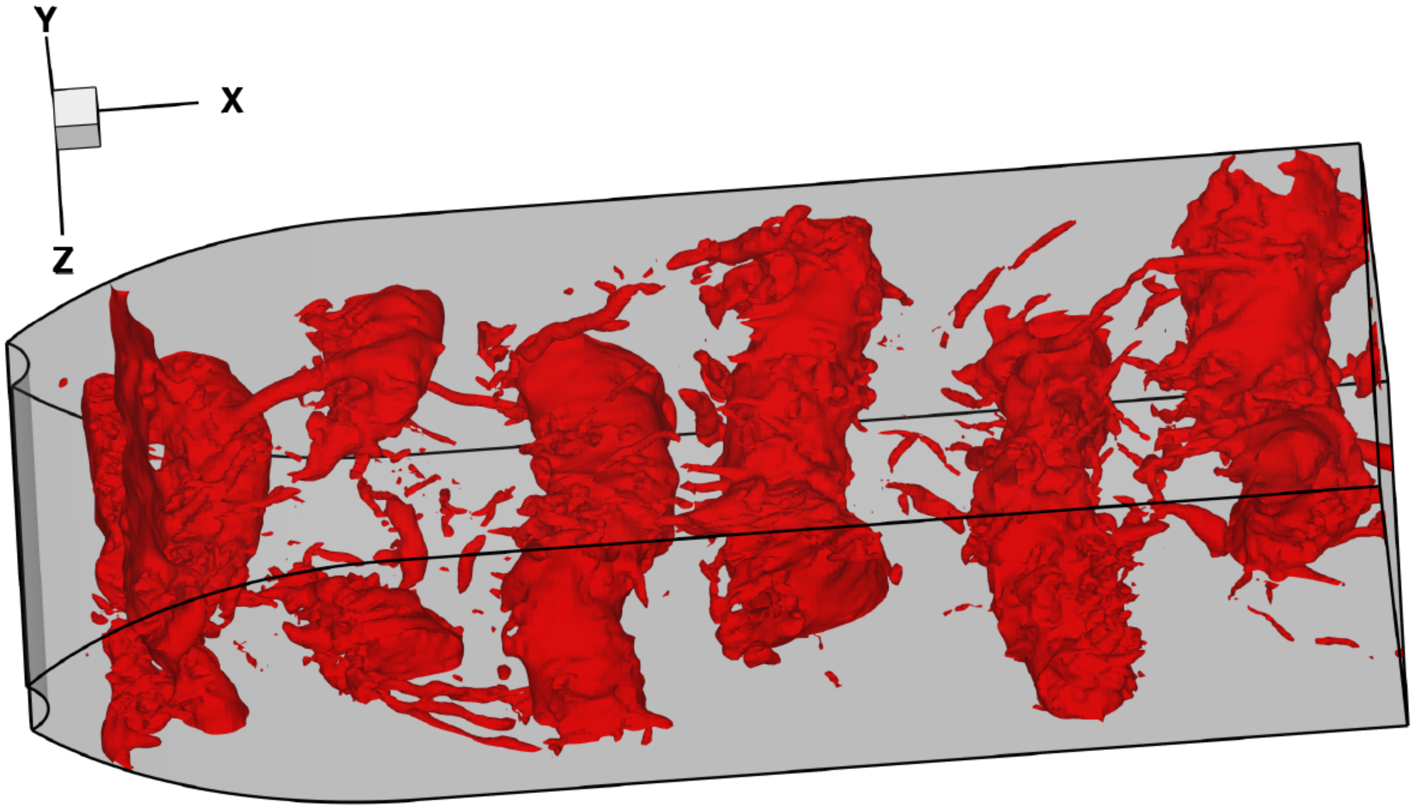
  - Explore reasons behind "slow assimilation" when θ/D is large

- Wake investigation published in 3 JFM articles (Vols. 724 (2013), 756 (2014) & 774 (2015)).

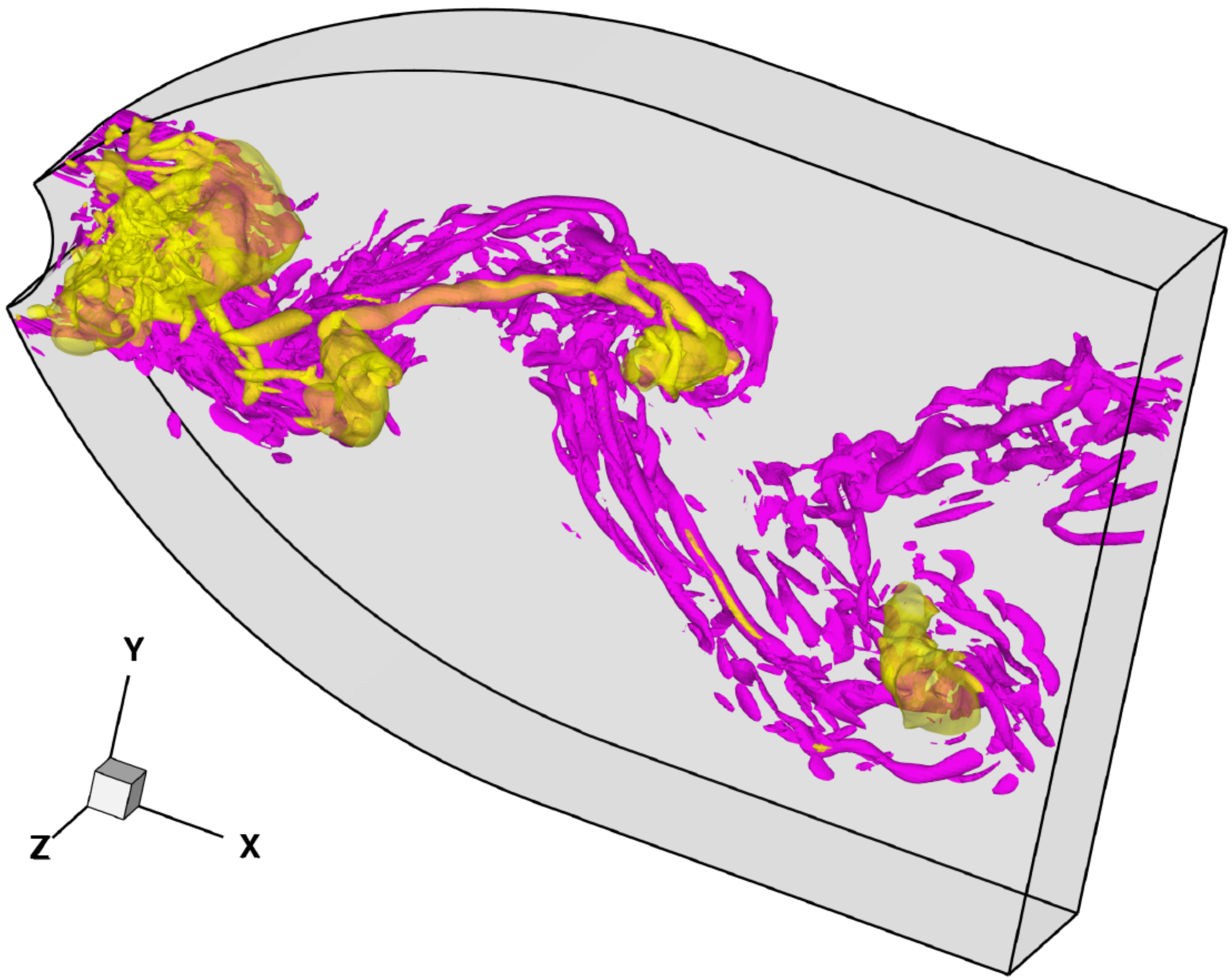


INSTANTANEOUS SPANWISE VORTICITY CONTOURS
(T/Tp = 6.35)
A
B
X
X
n = 11110, z/D = 1.125
y/D
x/D
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.5
0.0
0.5
1.0
1.5

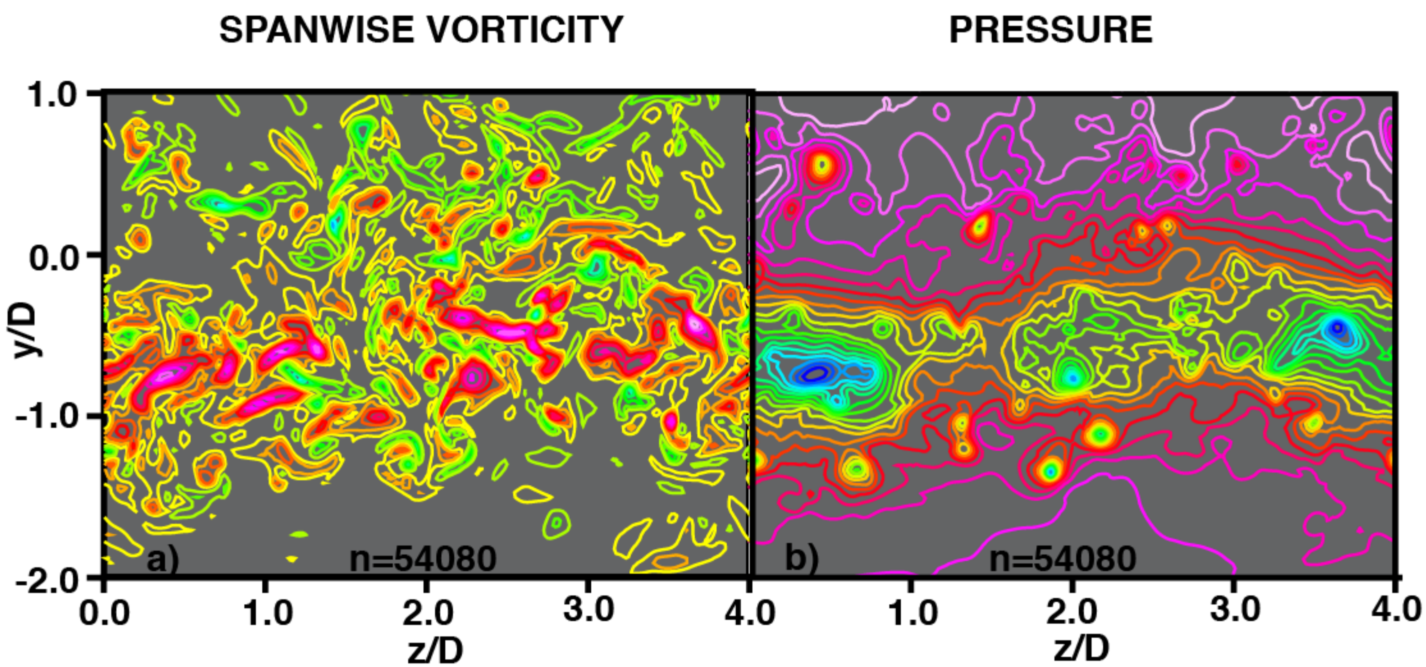
SURFACES OF CONSTANT PRESSURE SHOWING RIB AND SHED VORTICES



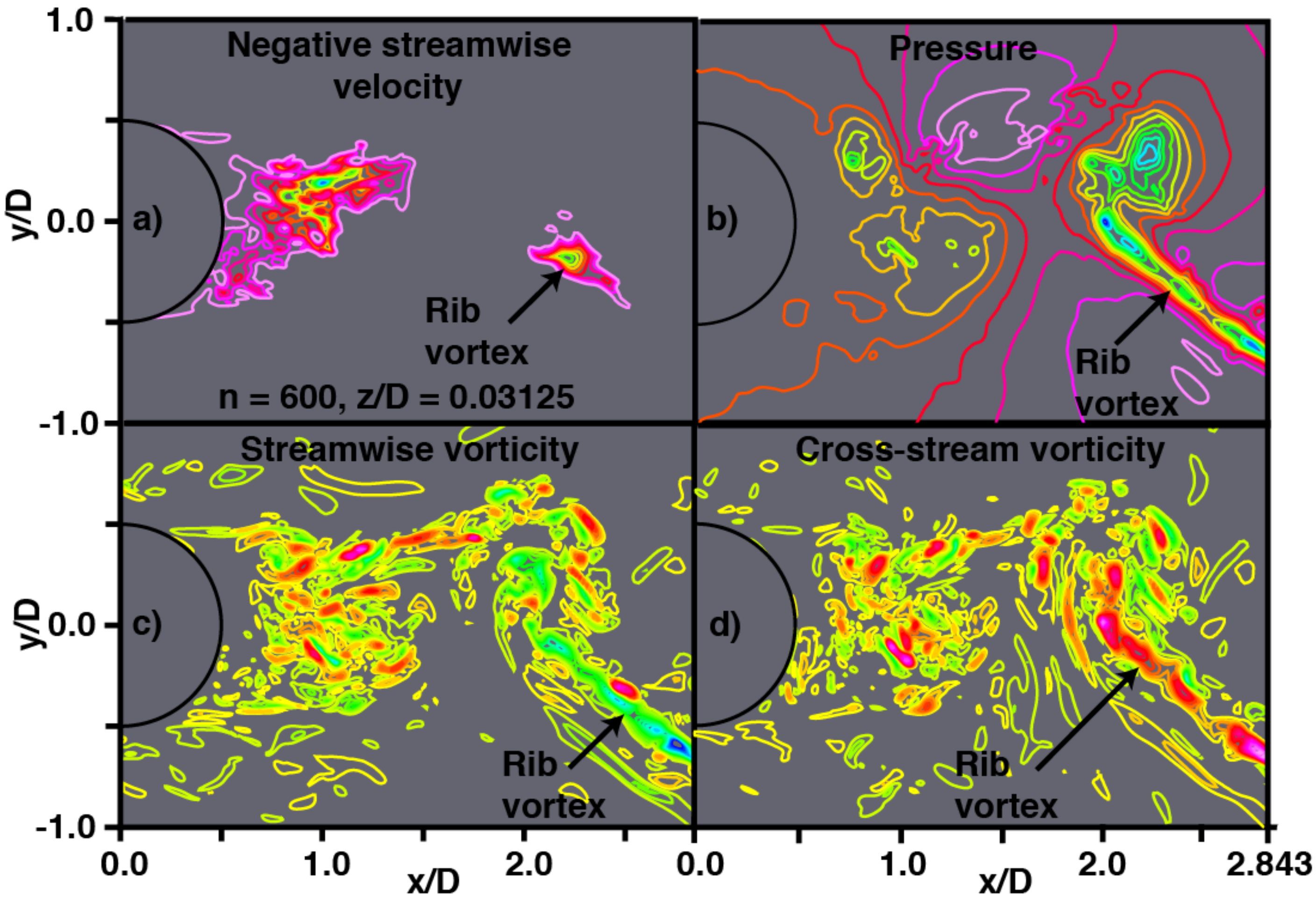
SURFACES OF CONSTANT VORTICITY MAGNITUDE AND PRESSURE SHOWING RIB AND SHED VORTICES



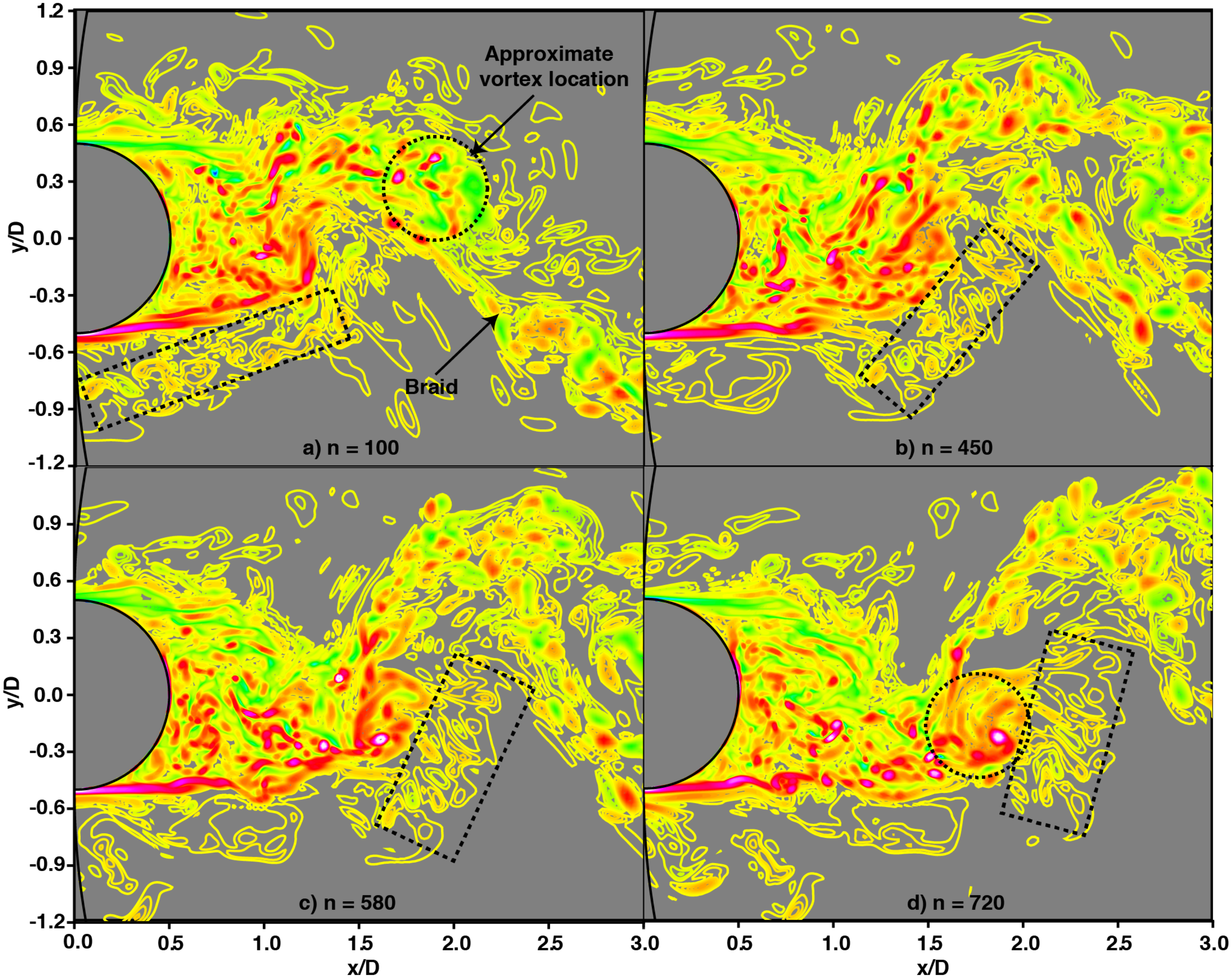
CROSS-SECTION THROUGH A SHED VORTEX
((Y, Z) PLANE)



CONTOURS OF NEGATIVE STREAMWISE VELOCITY, PRESSURE, STREAMWISE AND CROSS-STREAM VORTICITY IN A (x, y) PLANE



CONTOURS OF INSTANTANEOUS SPANWISE VORTICITY SHOWING ASSIMILATION OF LOG-LAYER EDDIES



HIGH PRESSURE TURBINE STAGE

Numerical Methodology In ROTORDNS

- High-order accurate integration method

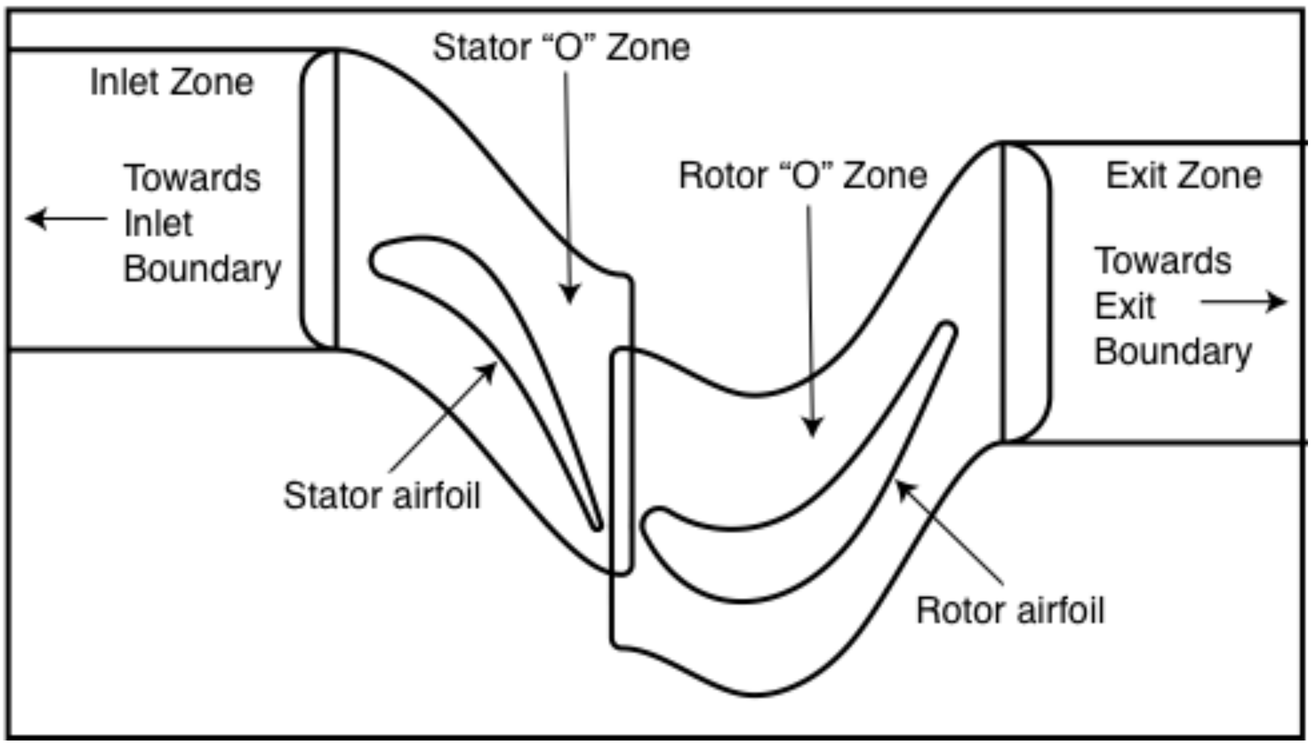
    - Convective terms are evaluated using fifth-order accurate upwind-biased finite-differences in the interior
    - Viscous terms are evaluated using fourth-order accurate central differences in the interior
    - Spatial order of accuracy is lowered near the boundaries

- Iterative implicit time-stepping

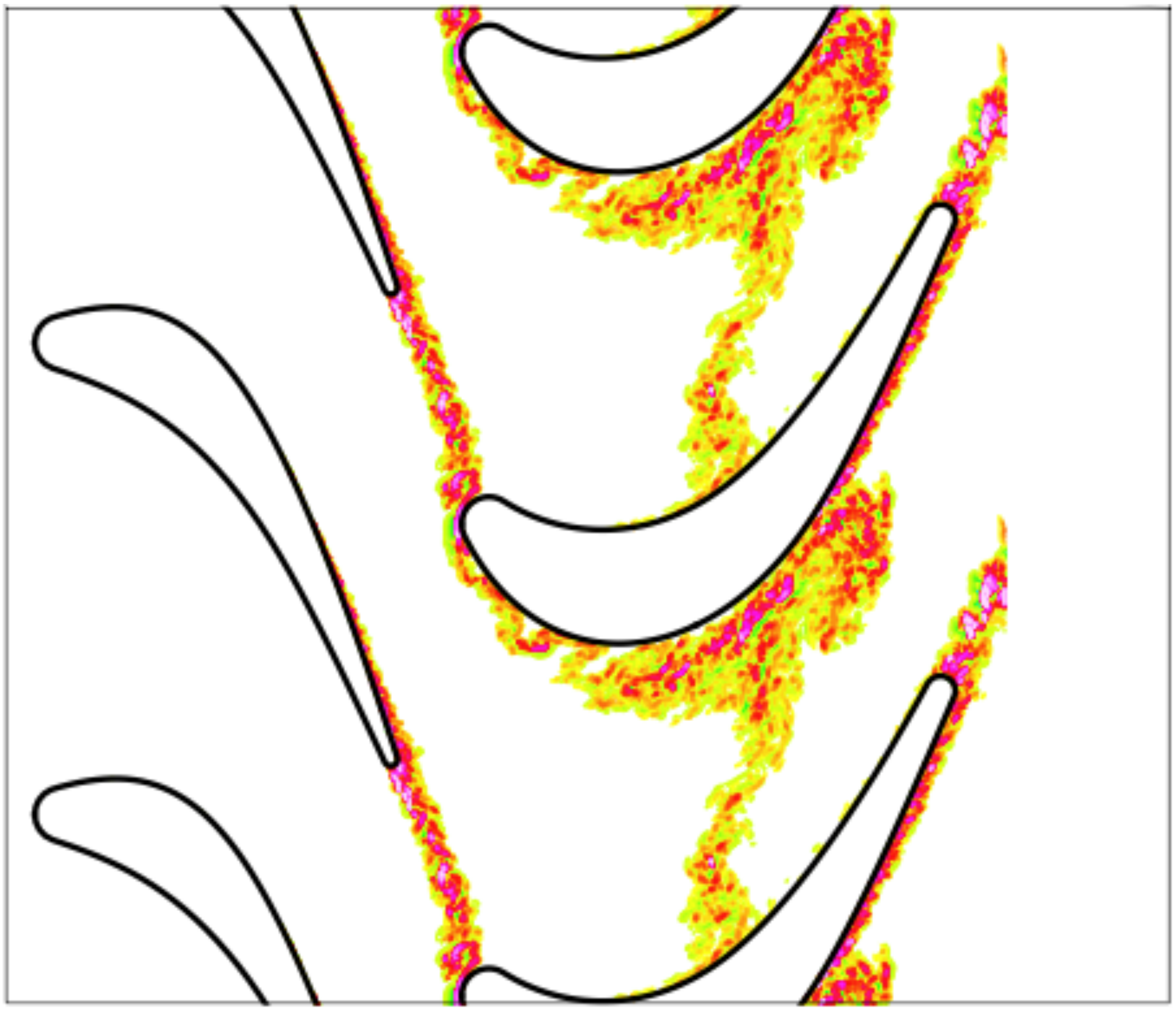
    - Multiple iterations at each time step
    - Linearization and factorization errors can be driven to zero at each time step
    - Fully implicit form of the difference equations are solved at each time step
    - Second-order accurate in time

- Multiple zone framework is used to simplify grid generation and provide adequate resolution where required

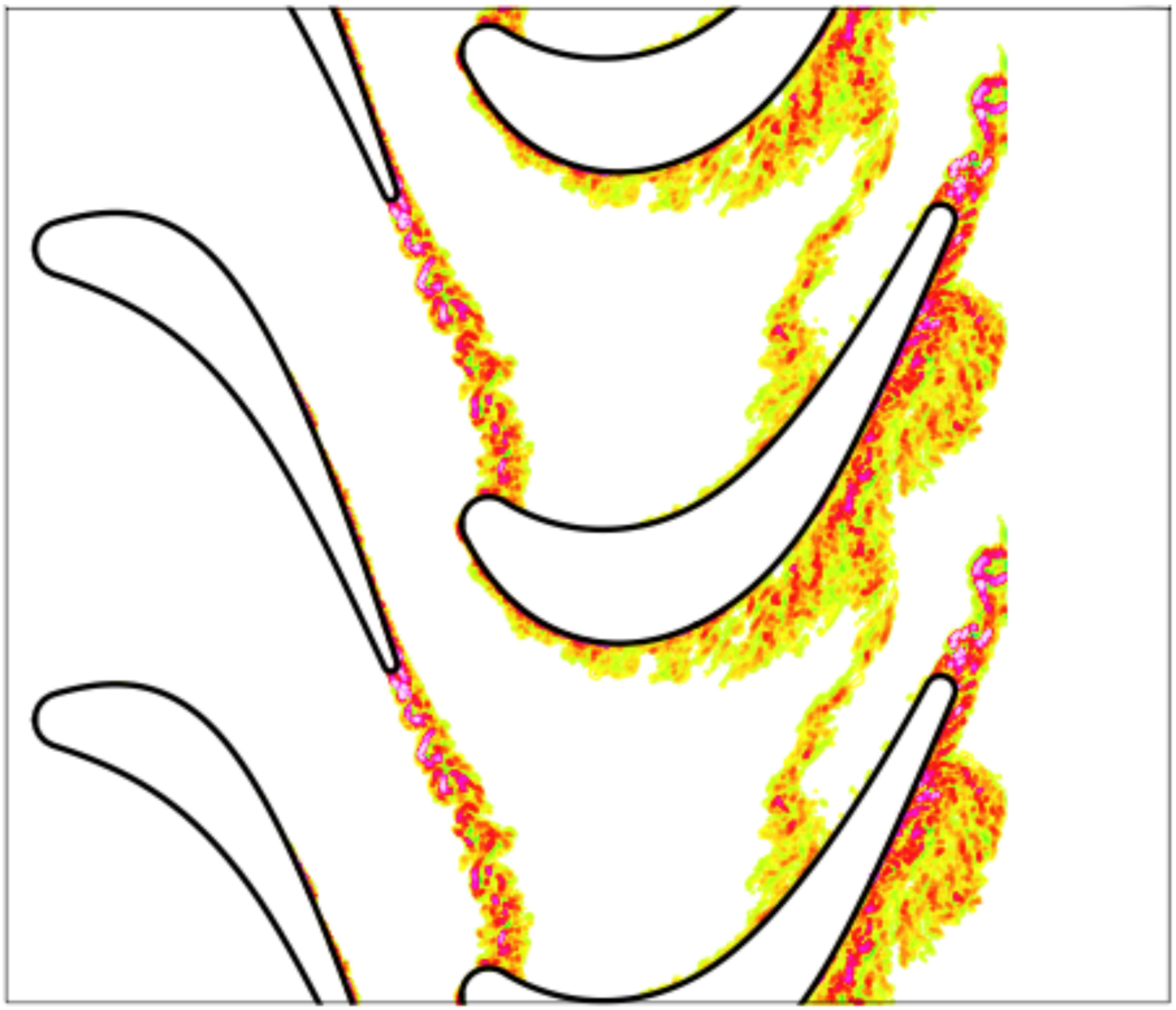
Stator-Rotor Geometry and Computational Zones
(Stator Rescaled by the Factor 22/28)



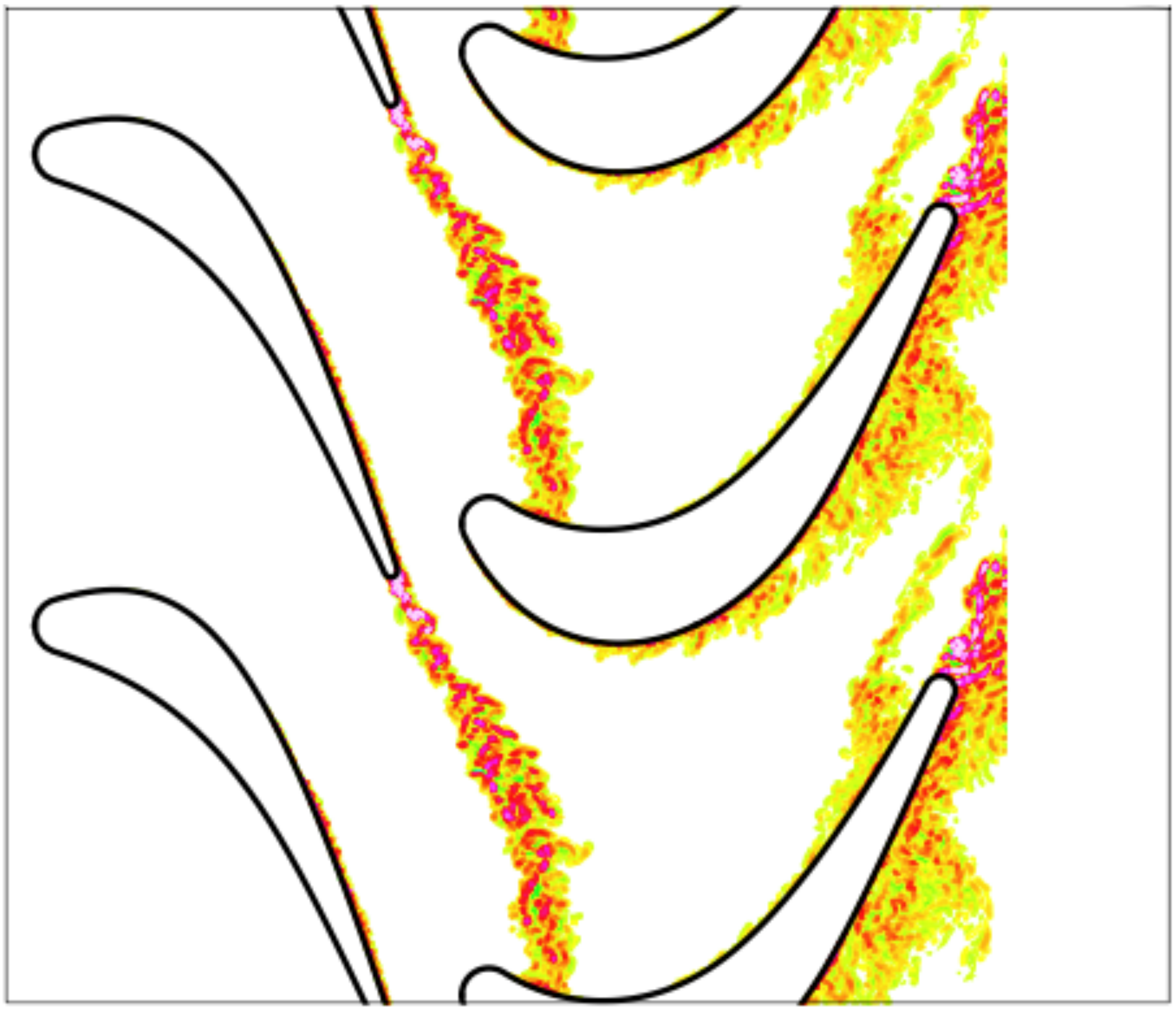
Instantaneous Contours of Spanwise Velocity in the Stage ($\phi = 0.5$)



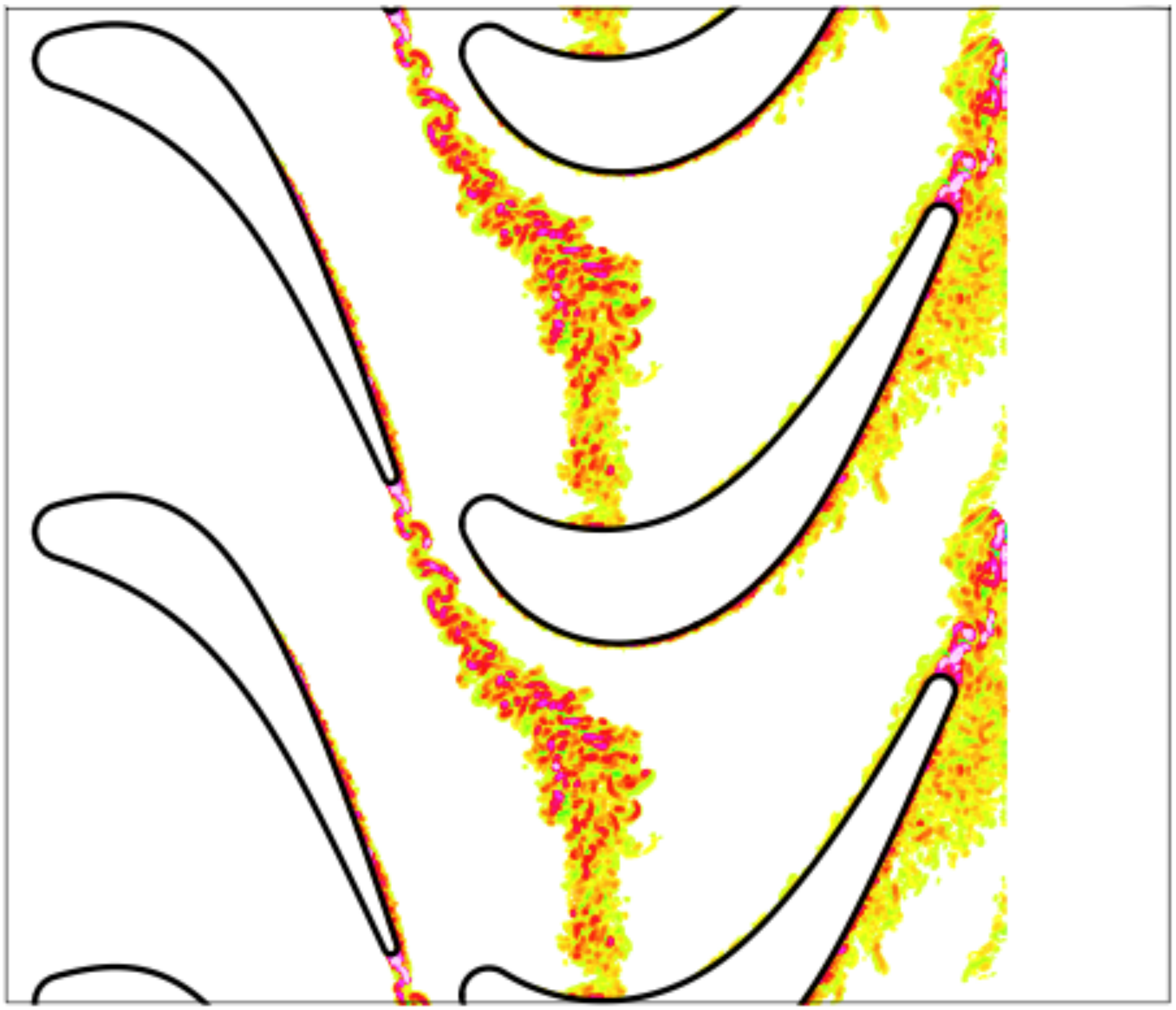
Instantaneous Contours of Spanwise Velocity in the Stage (ϕ = 0.7)



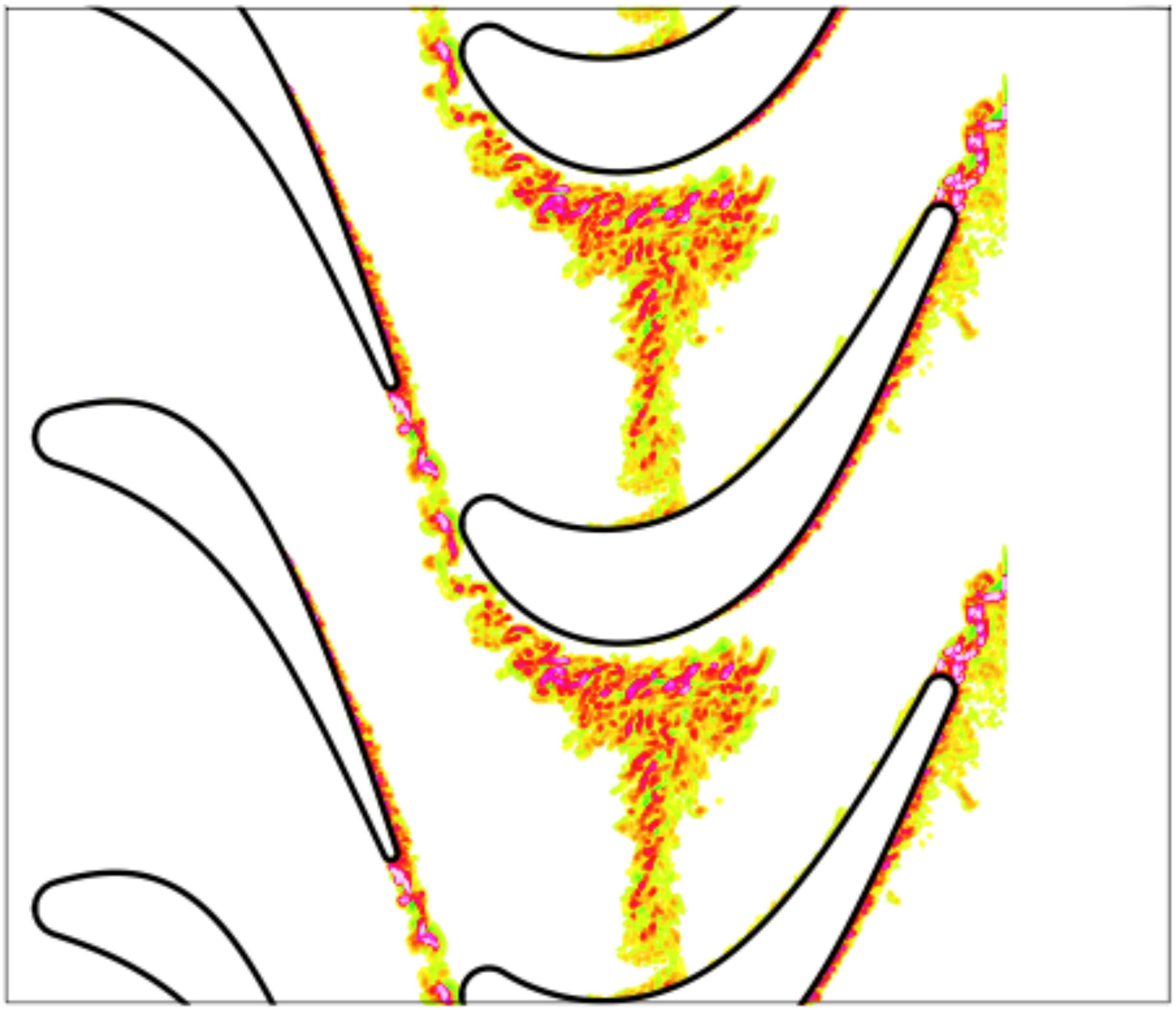
Instantaneous Contours of Spanwise Velocity in the Stage (ϕ = 0.9)



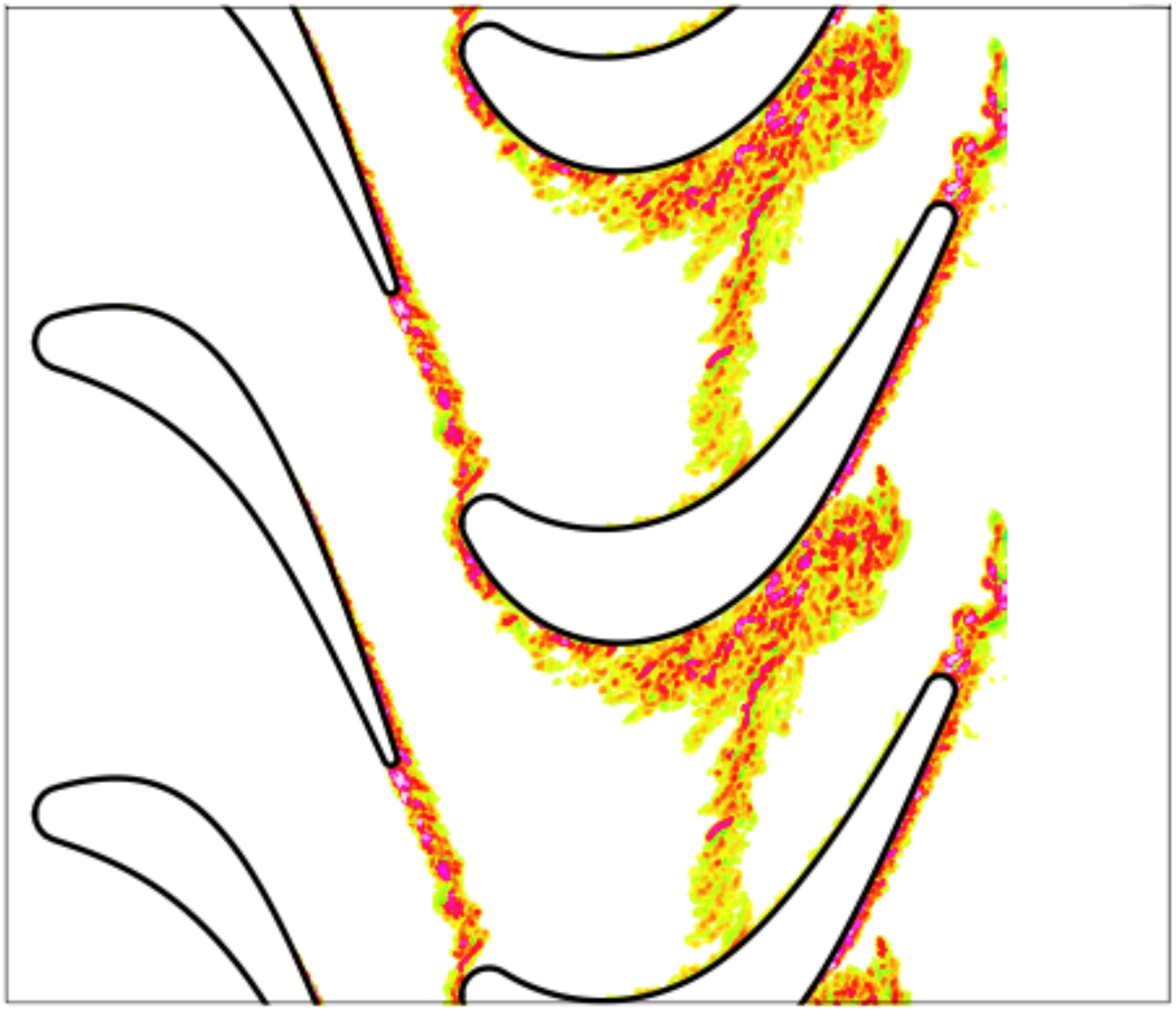
Instantaneous Contours of Spanwise Velocity in the Stage (ϕ = 1.1)



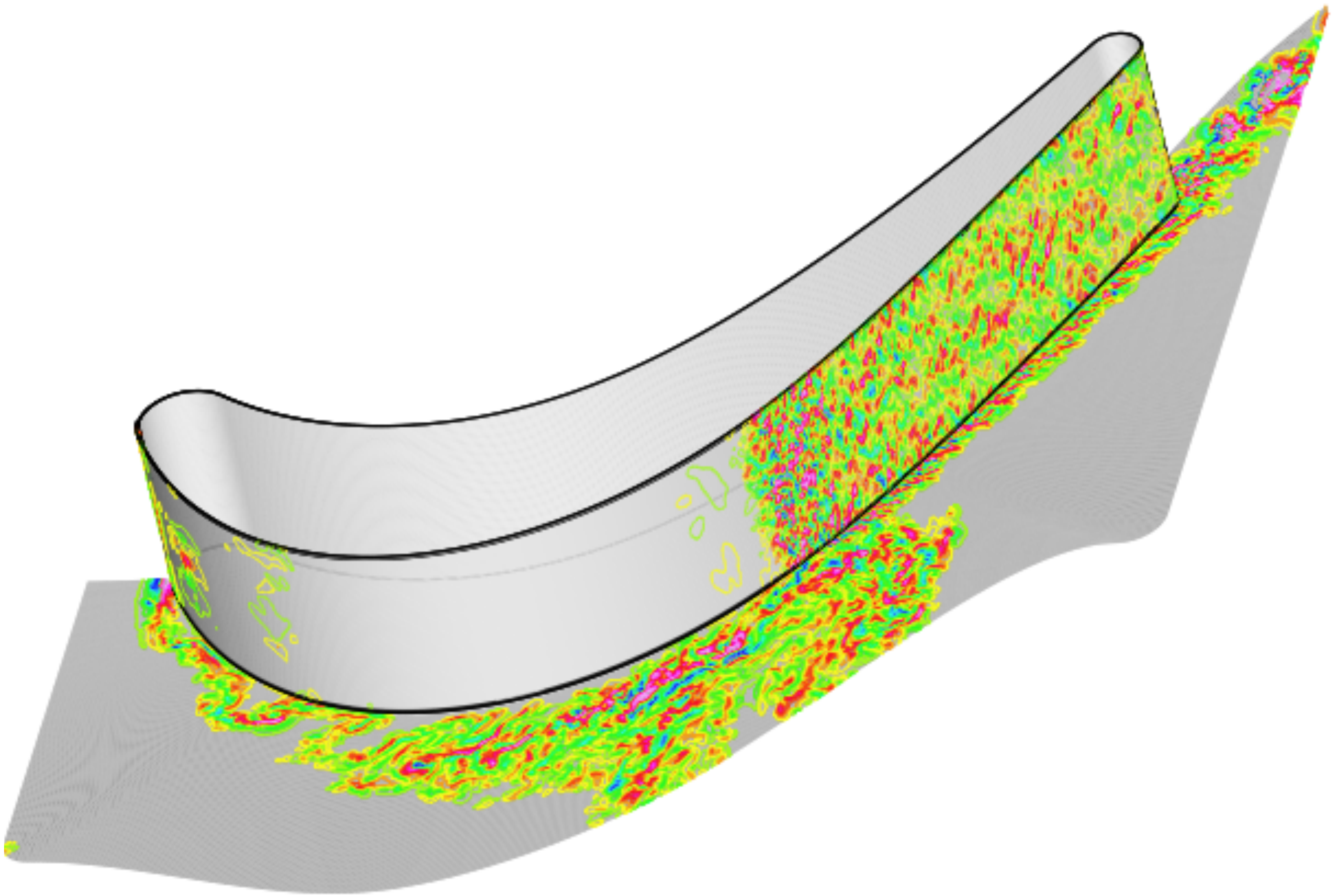
Instantaneous Contours of Spanwise Velocity in the Stage (ϕ = 1.3)



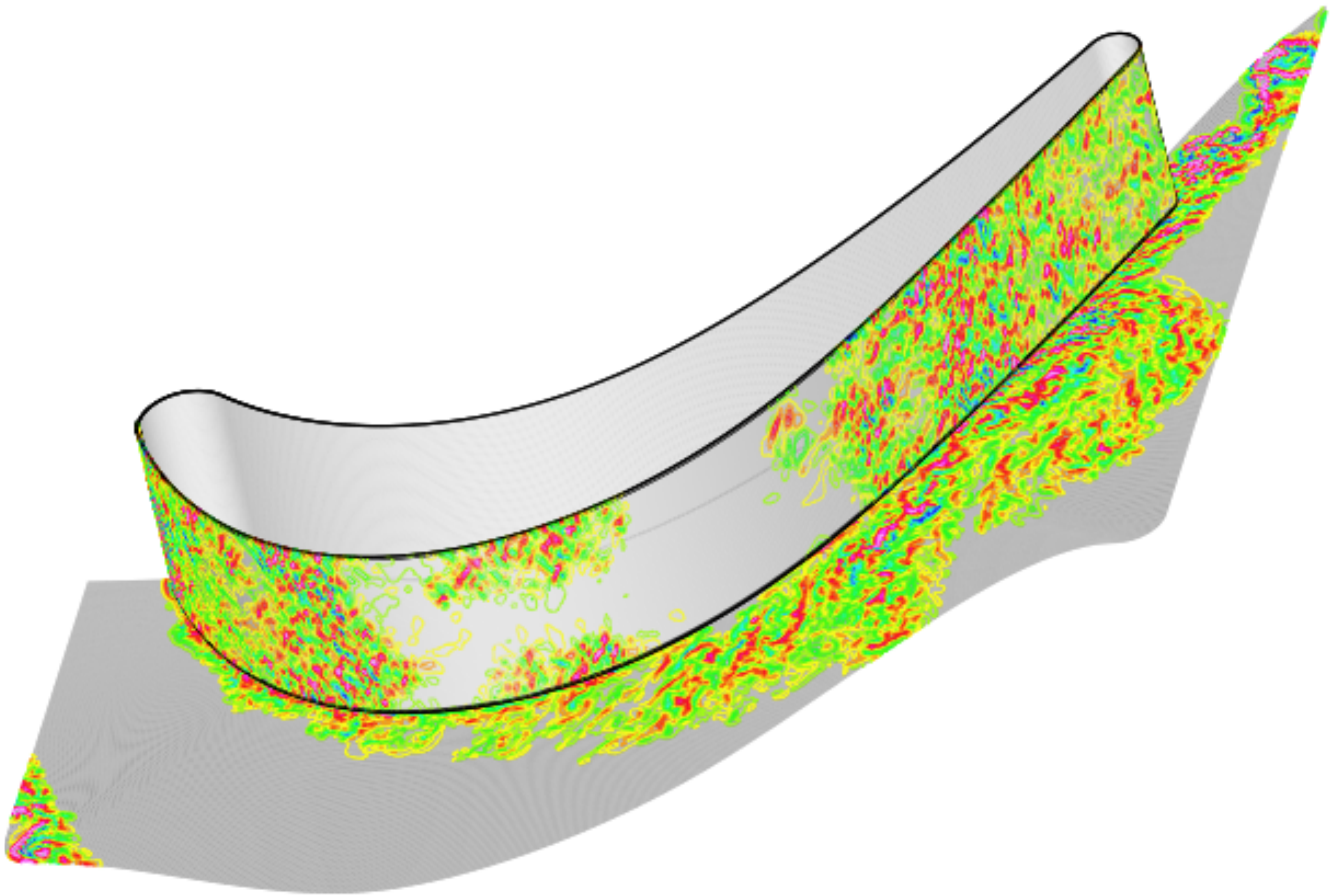
Instantaneous Contours of Spanwise Velocity in the Stage (ϕ = 1.5)



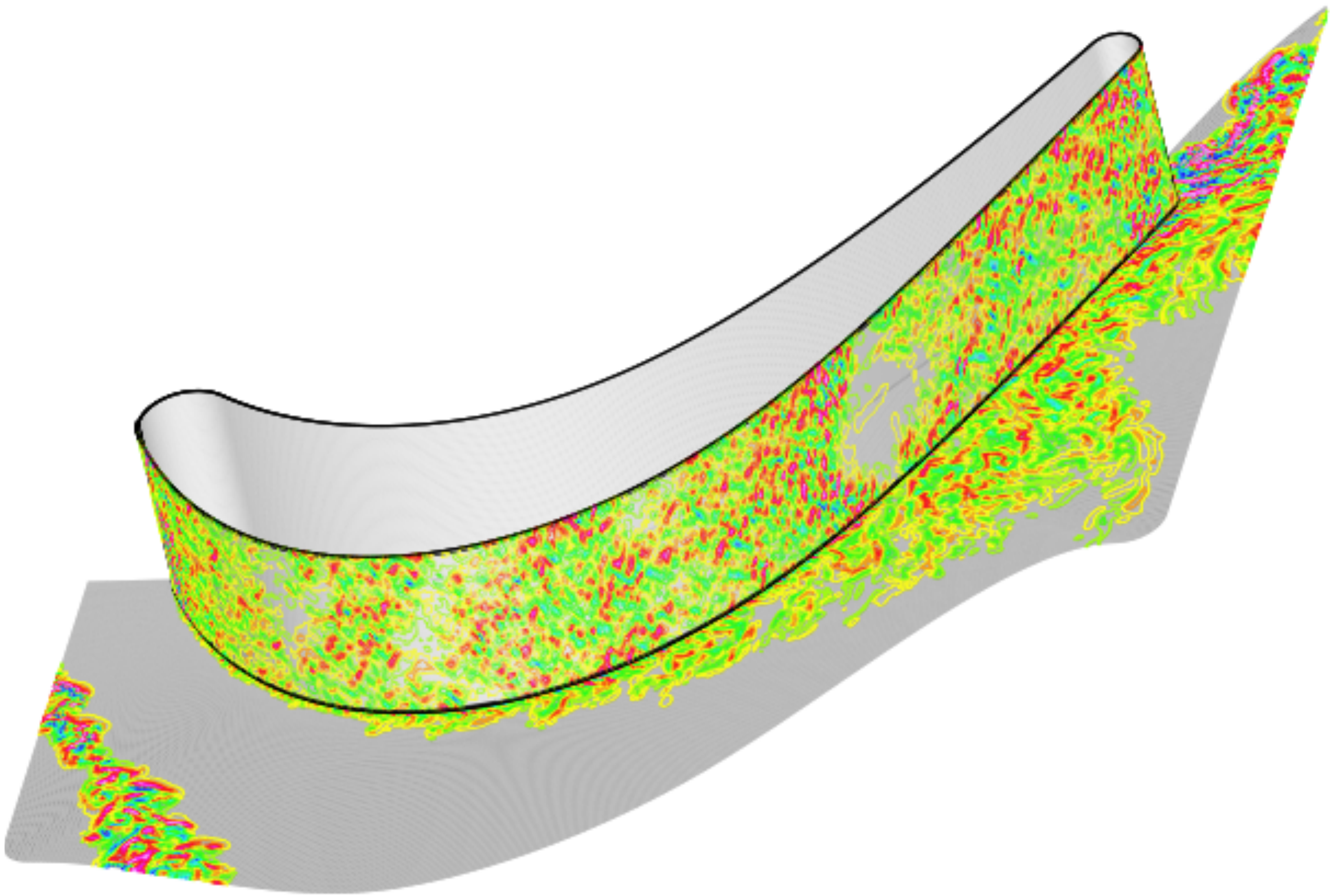
Instantaneous Contours of Spanwise Velocity above the Rotor Suction Surface (ϕ = 0.5)



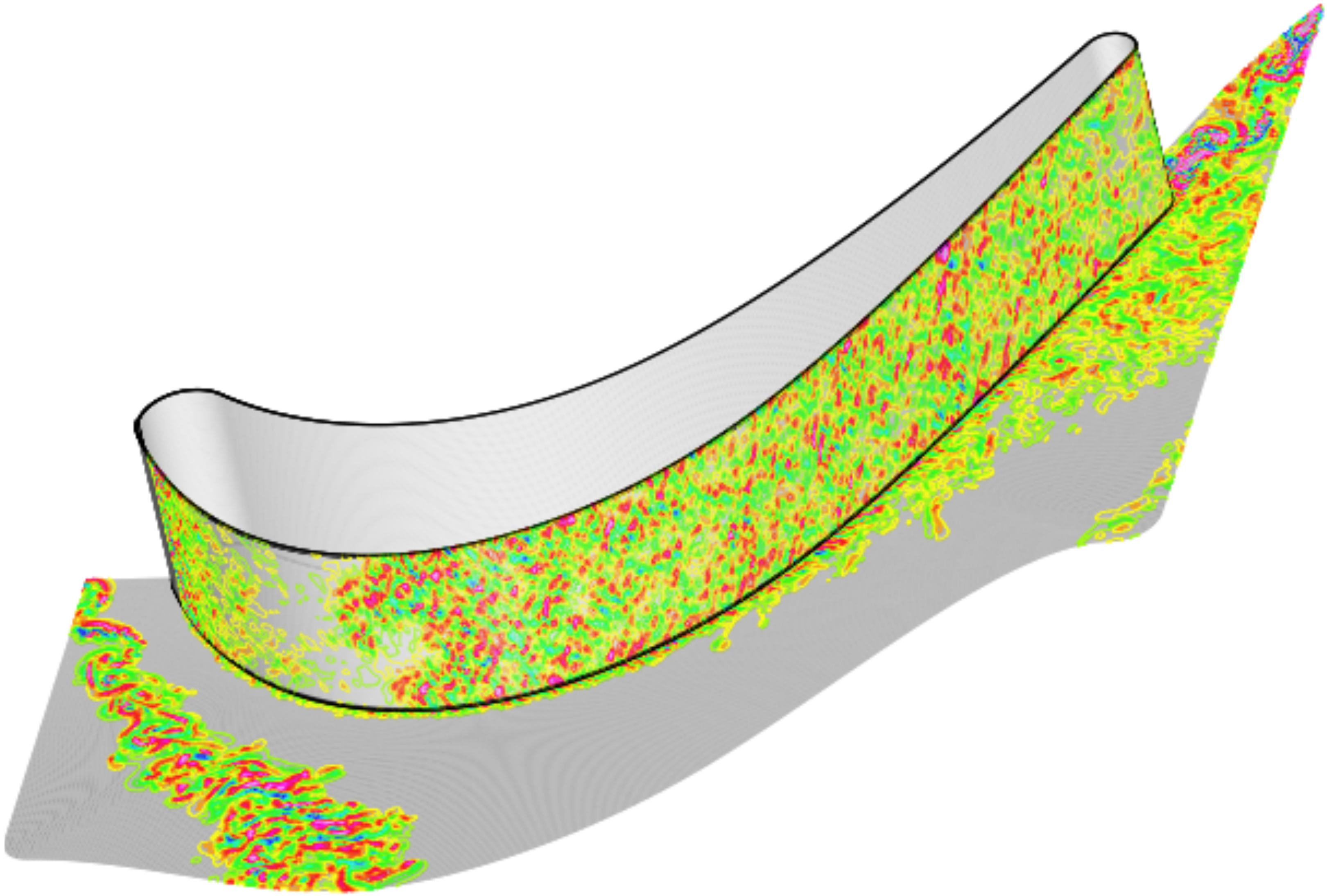
Instantaneous Contours of Spanwise Velocity above the Rotor Suction Surface (ϕ = 0.7)



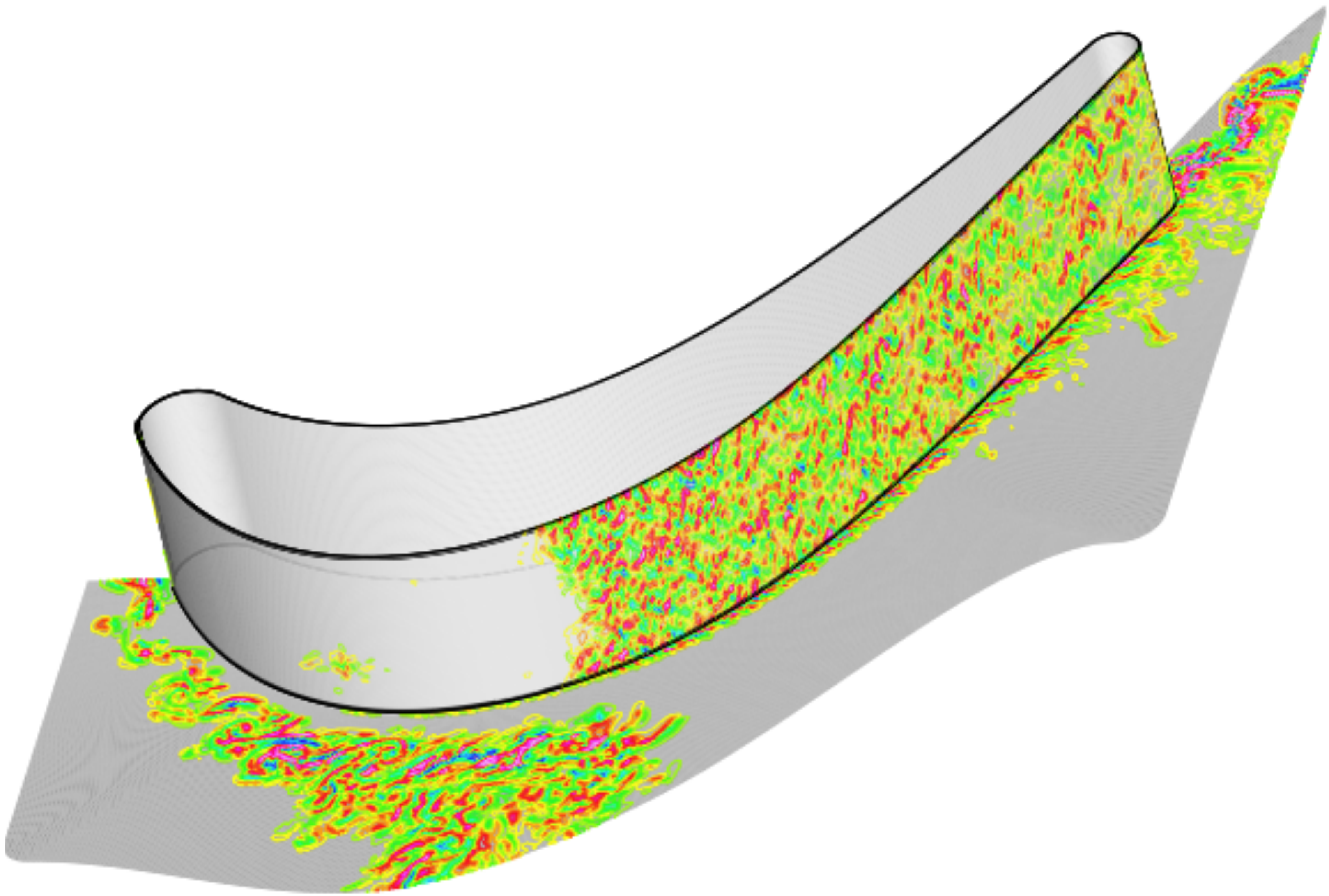
Instantaneous Contours of Spanwise Velocity above the Rotor Suction Surface (ϕ = 0.9)



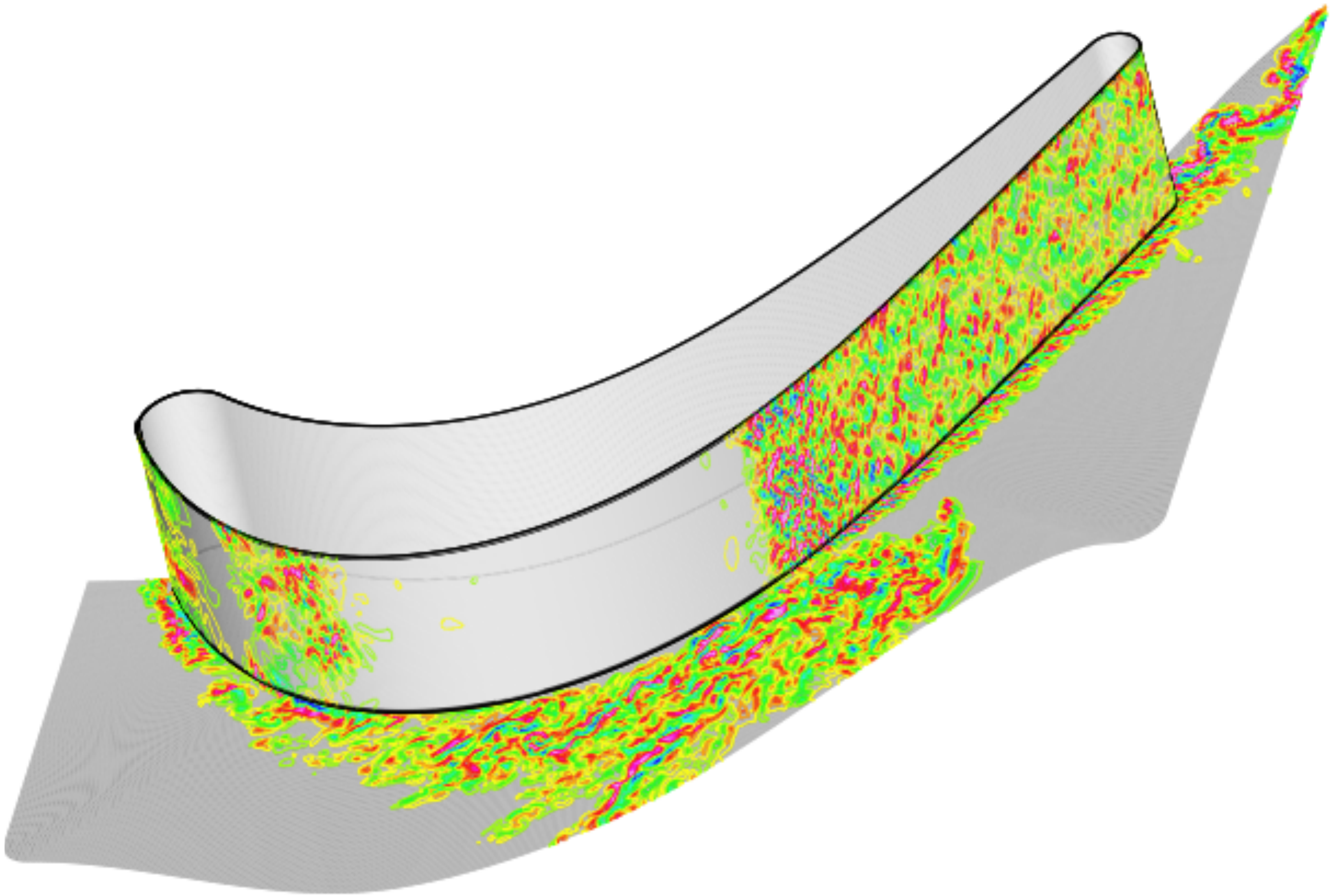
Instantaneous Contours of Spanwise Velocity above the Rotor Suction Surface (ϕ = 1.1)



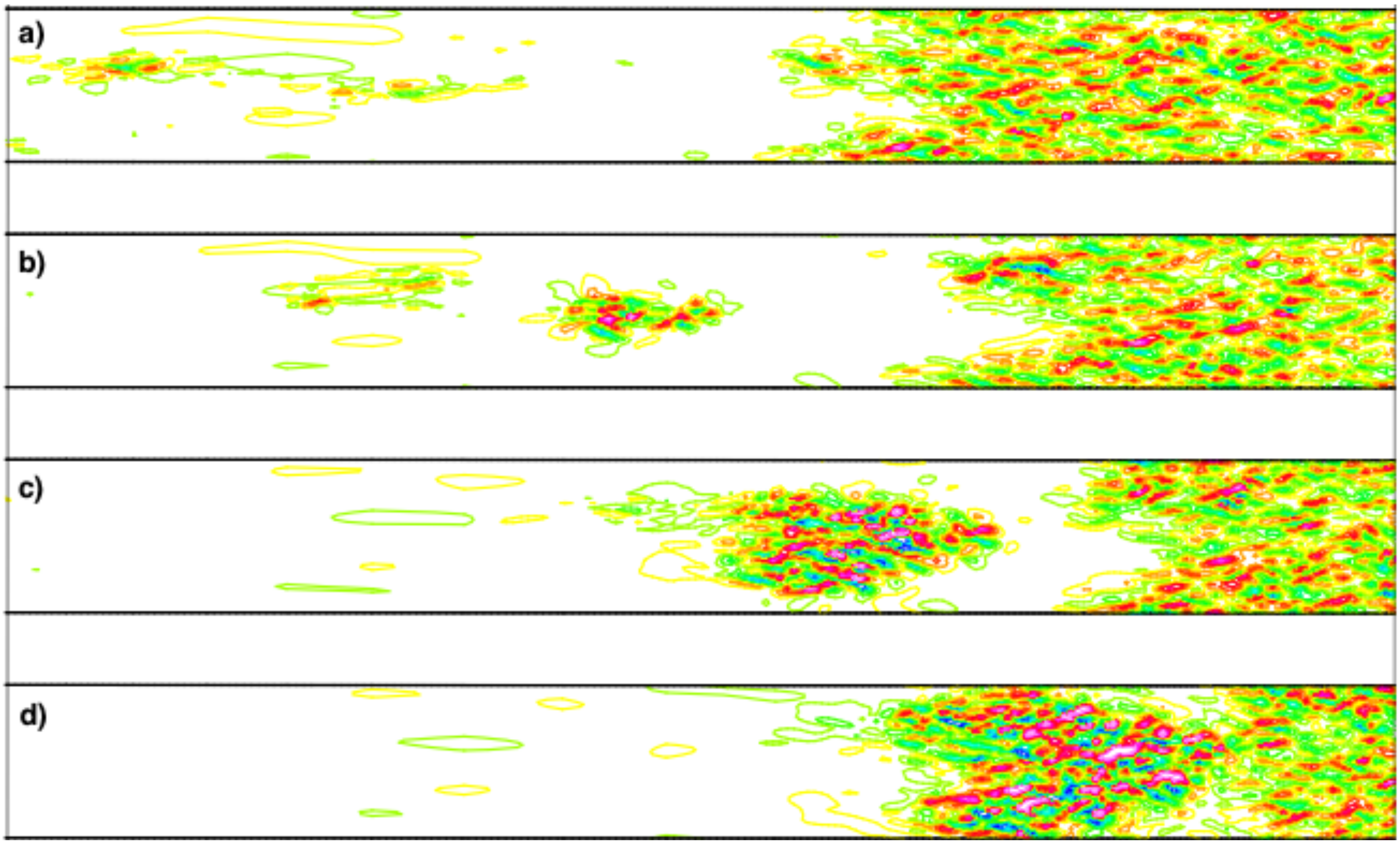
Instantaneous Contours of Spanwise Velocity above the Rotor Suction Surface (ϕ = 1.3)



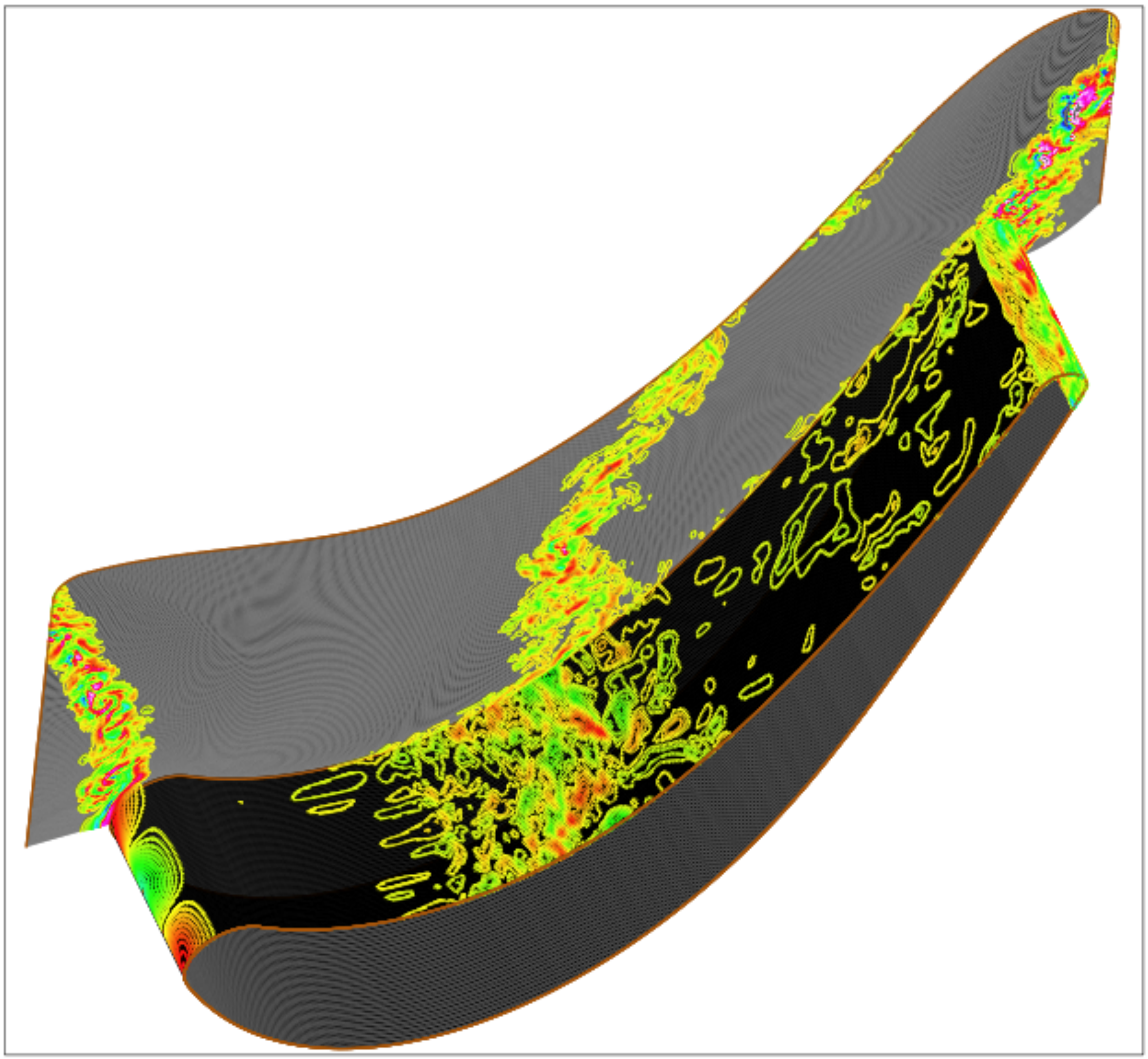
Instantaneous Contours of Spanwise Velocity above the Rotor Suction Surface (ϕ = 1.5)



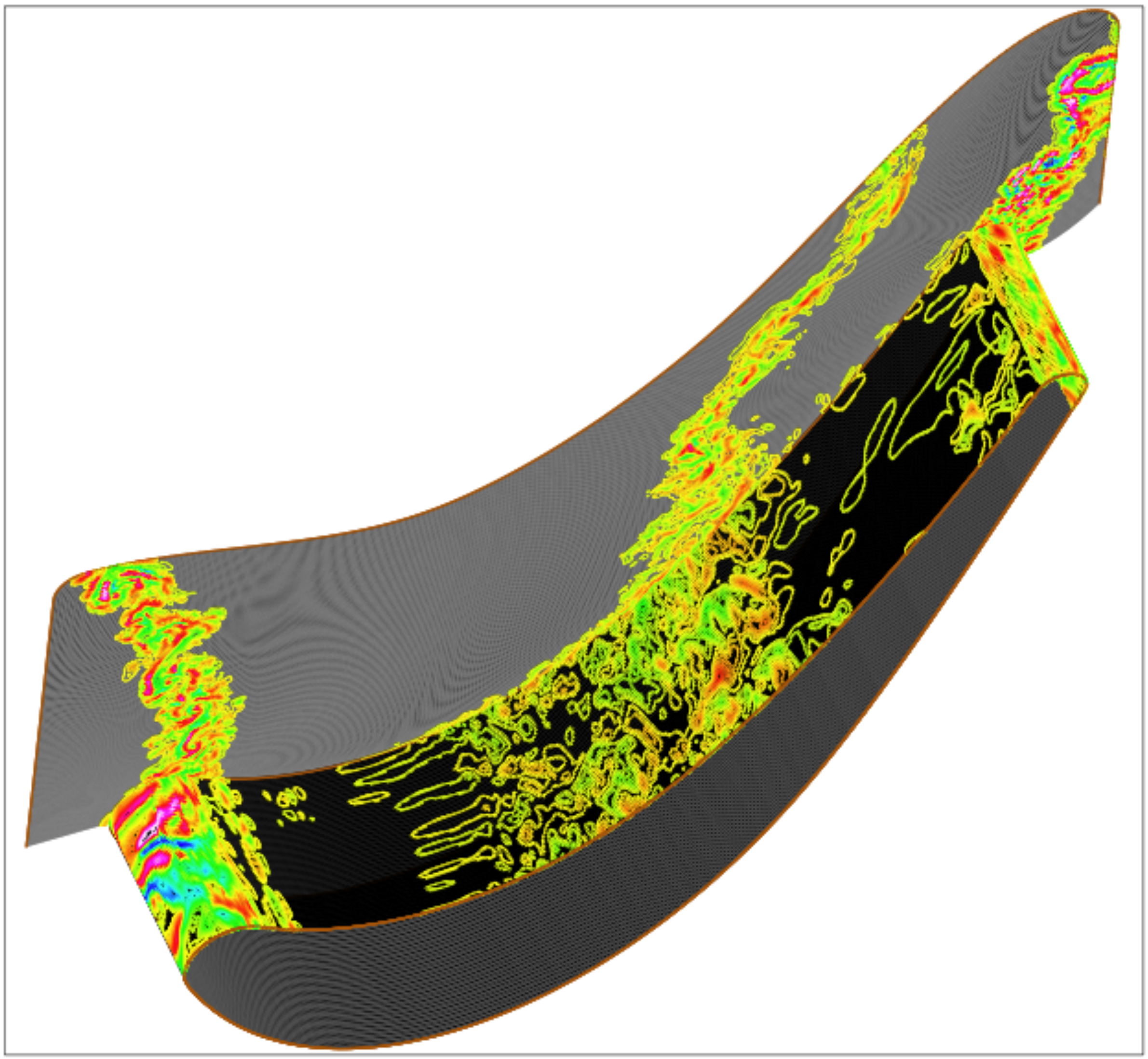
Instantaneous Contours of Spanwise Velocity on the Rotor Suction Surface
Showing evolution and Convection of Turbulent Spot
(ϕ = 1.22, 1.26, 1.30 & 1.34)



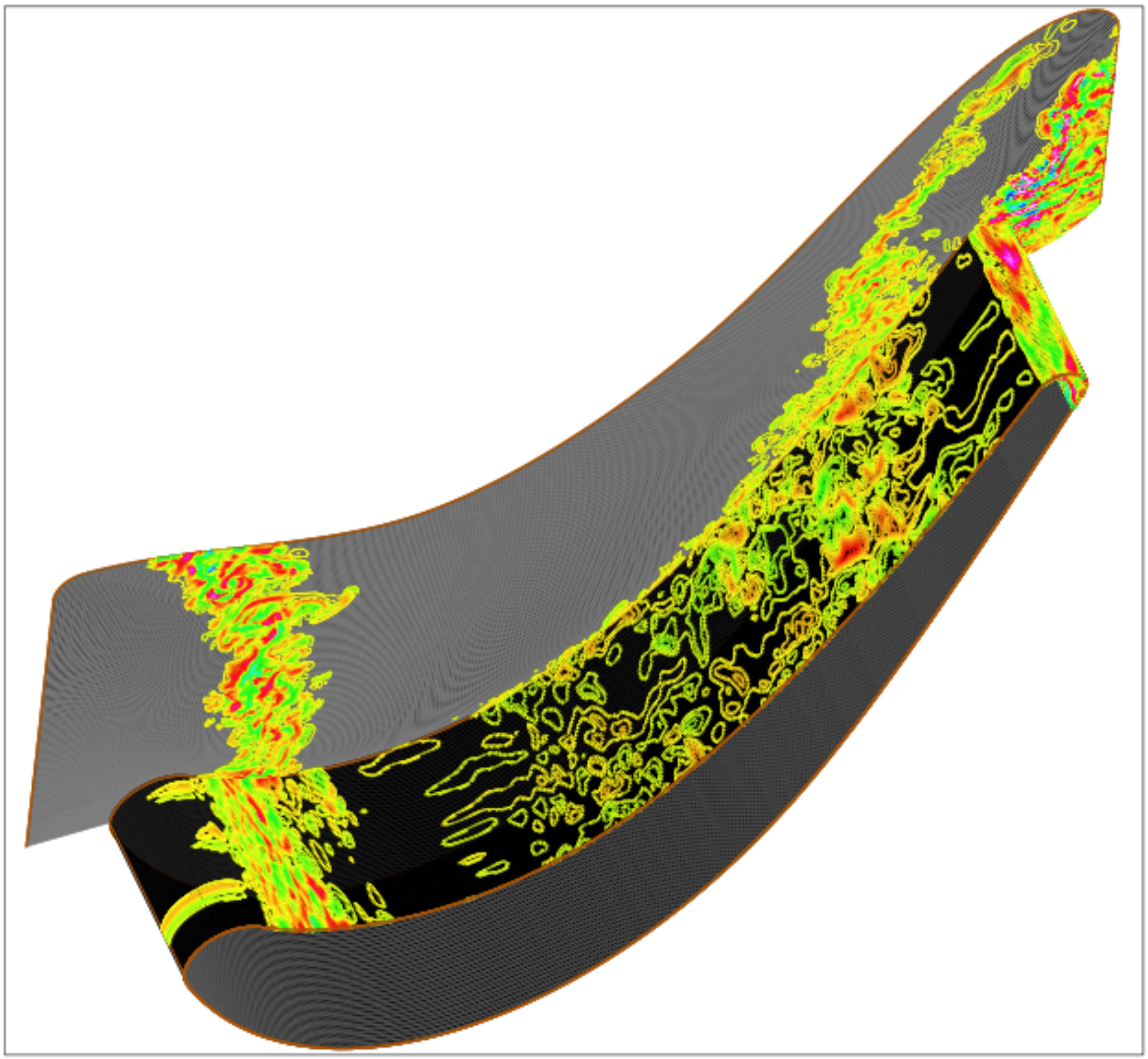
Instantaneous Contours of Spanwise Velocity above the Rotor Pressure Surface (ϕ = 0.5)



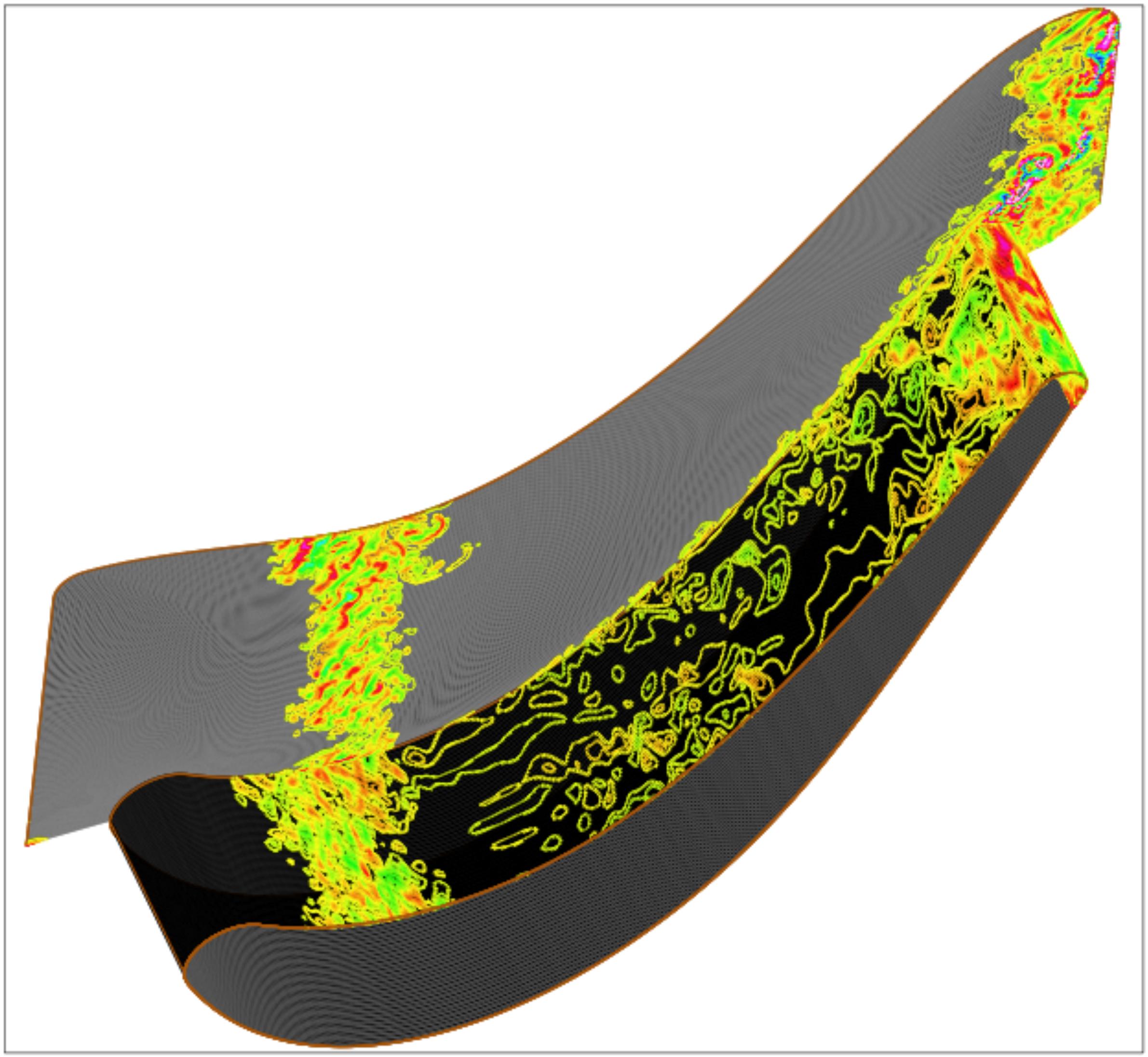
Instantaneous Contours of Spanwise Velocity above the Rotor Pressure Surface (ϕ = 0.7)



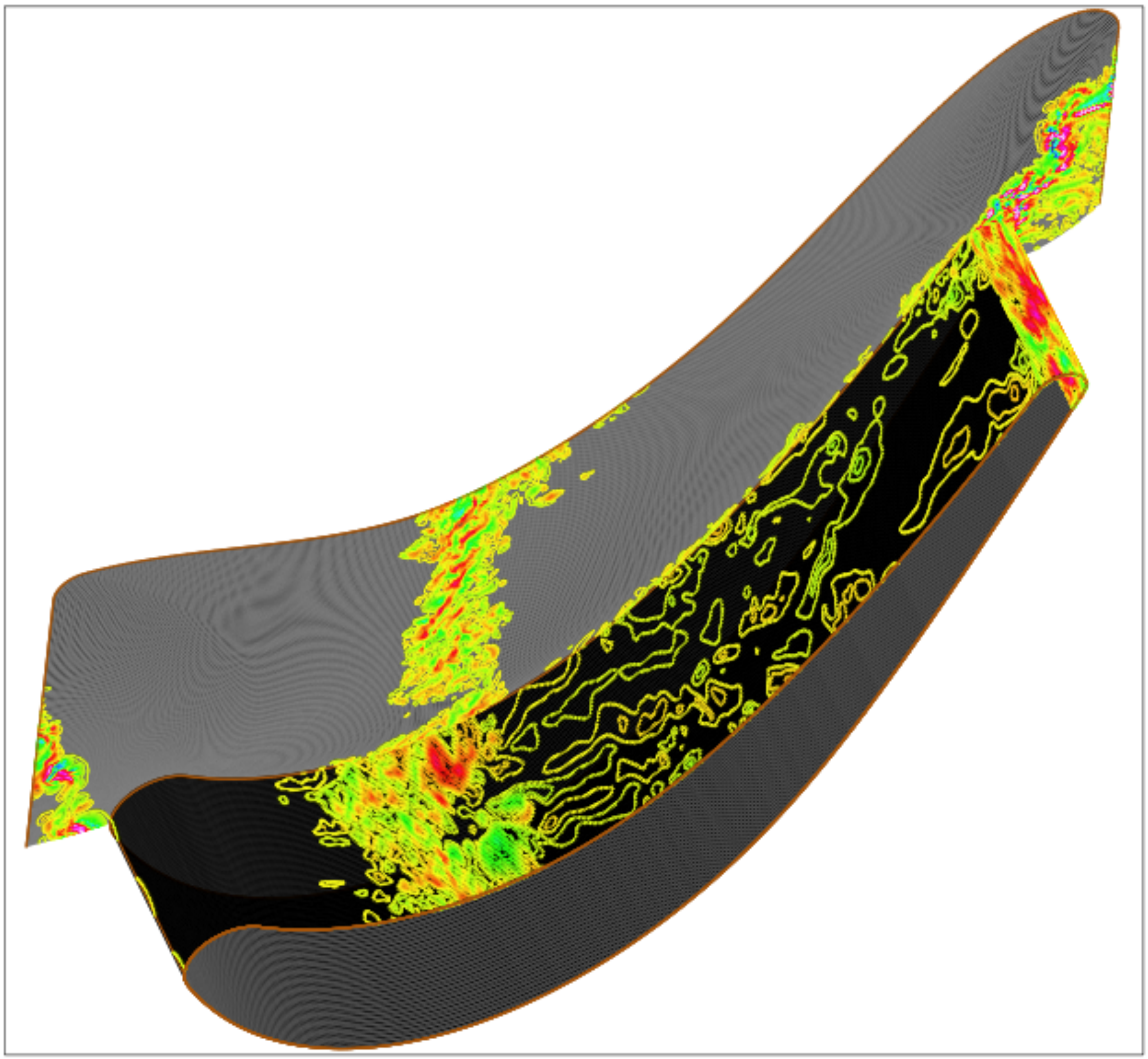
Instantaneous Contours of Spanwise Velocity above the Rotor Pressure Surface ($\phi = 0.9$)



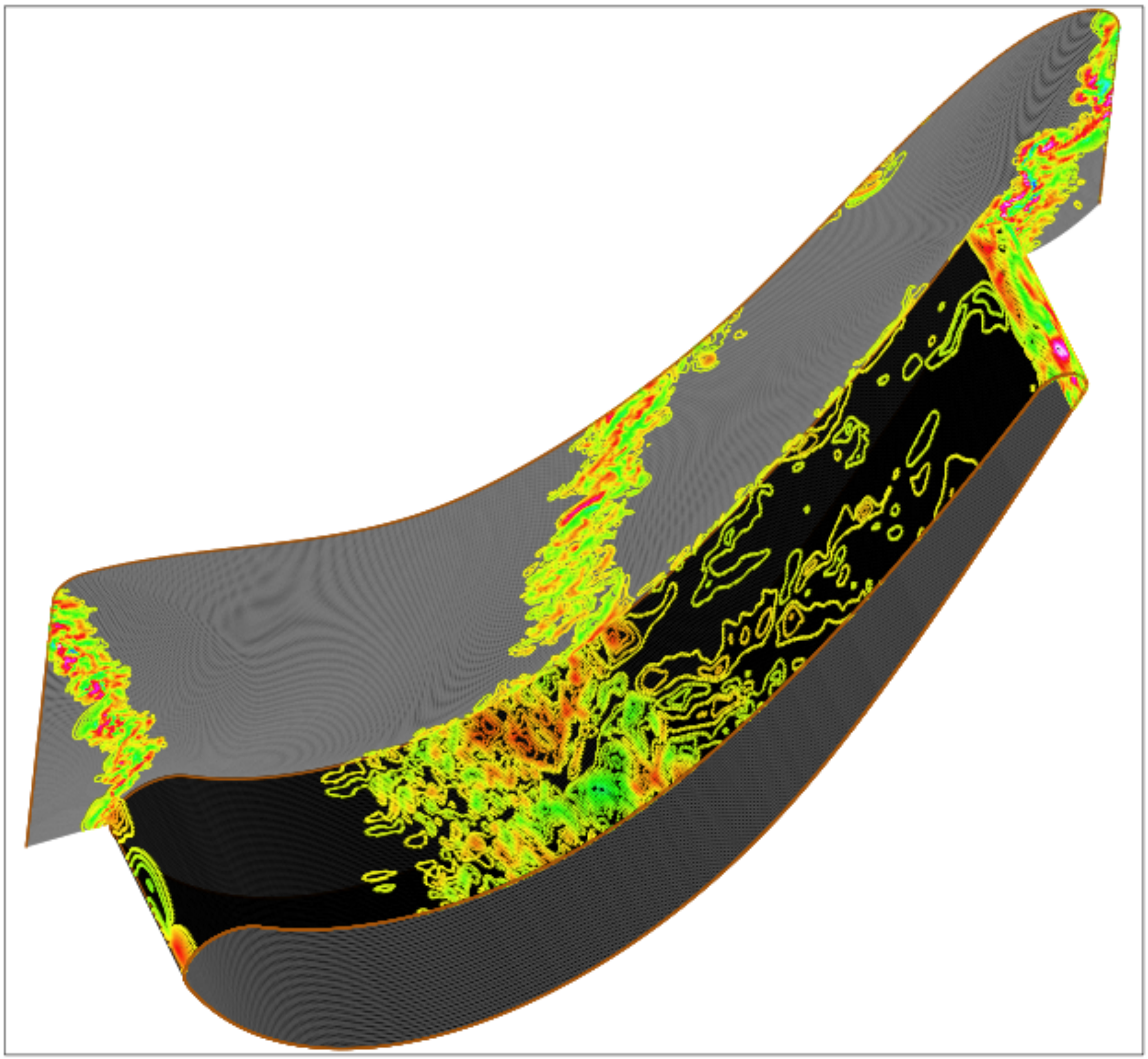
Instantaneous Contours of Spanwise Velocity above the Rotor Pressure Surface (ϕ = 1.1)



Instantaneous Contours of Spanwise Velocity above the Rotor Pressure Surface ($\phi = 1.3$)

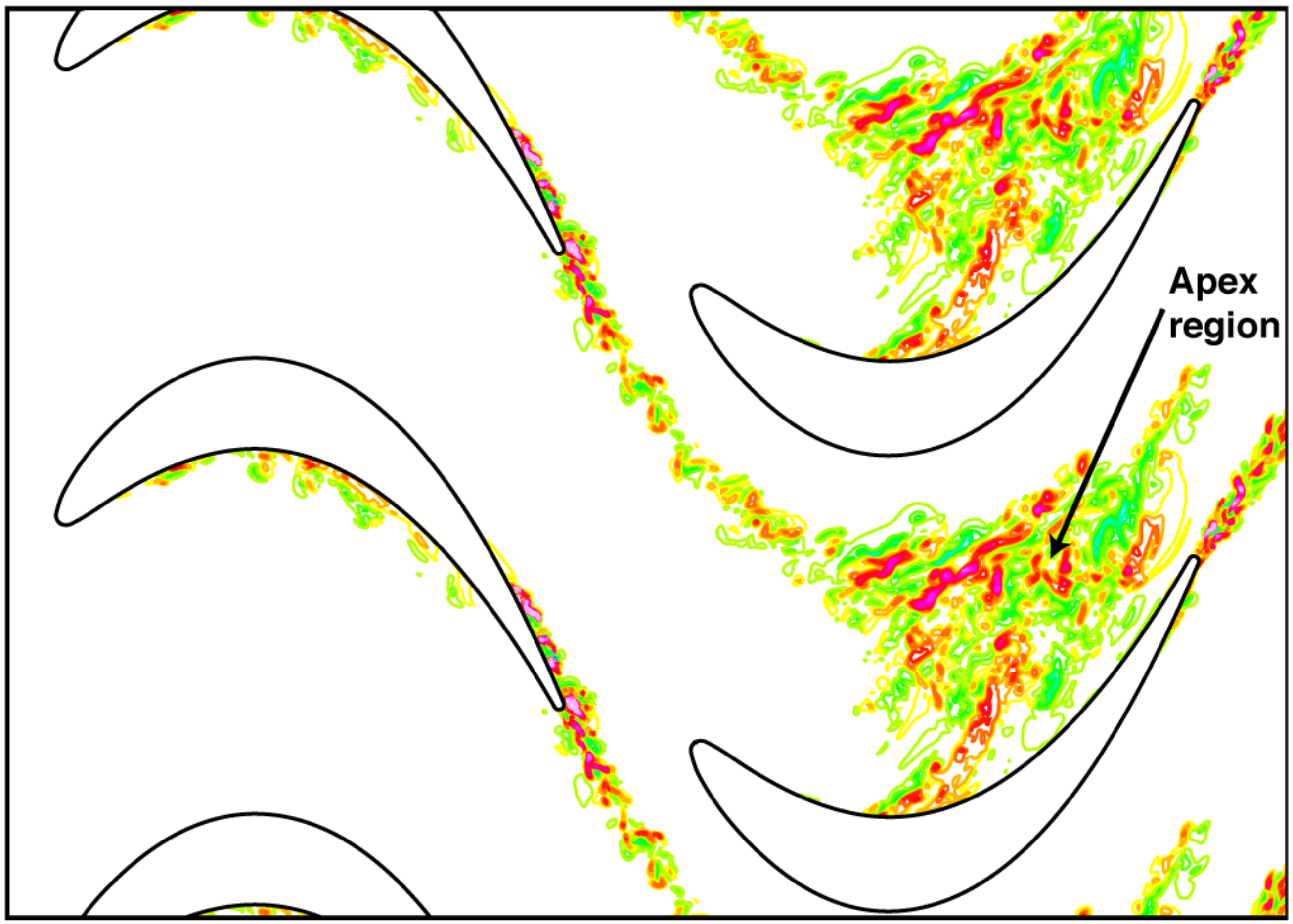


Instantaneous Contours of Spanwise Velocity above the Rotor Pressure Surface (ϕ = 1.5)

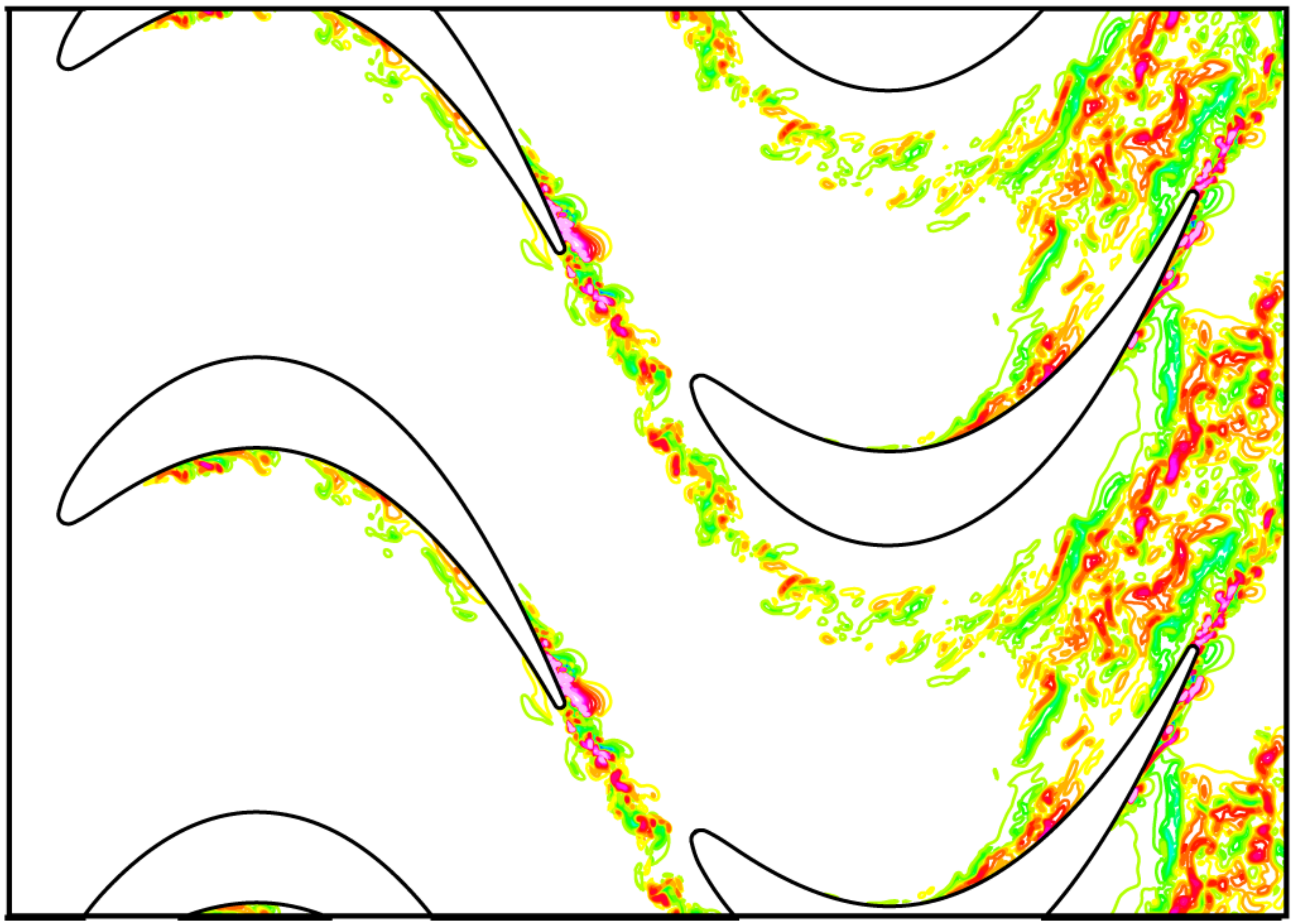


LOW PRESSURE TURBINE STAGE

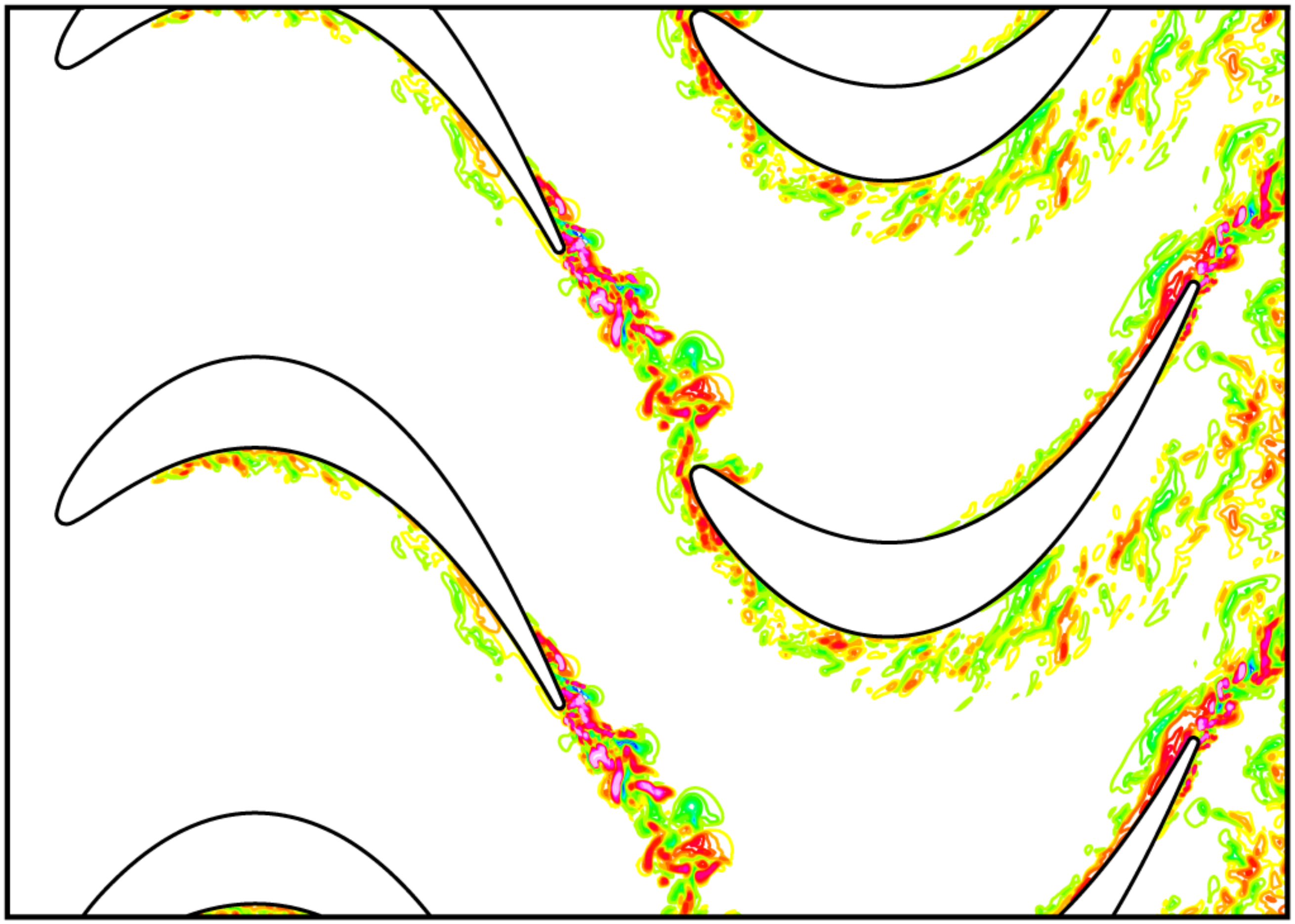
INSTANTANEOUS CONTOURS OF SPANWISE VELOCITY
(SIDE-VIEW, ϕ = 3.1)



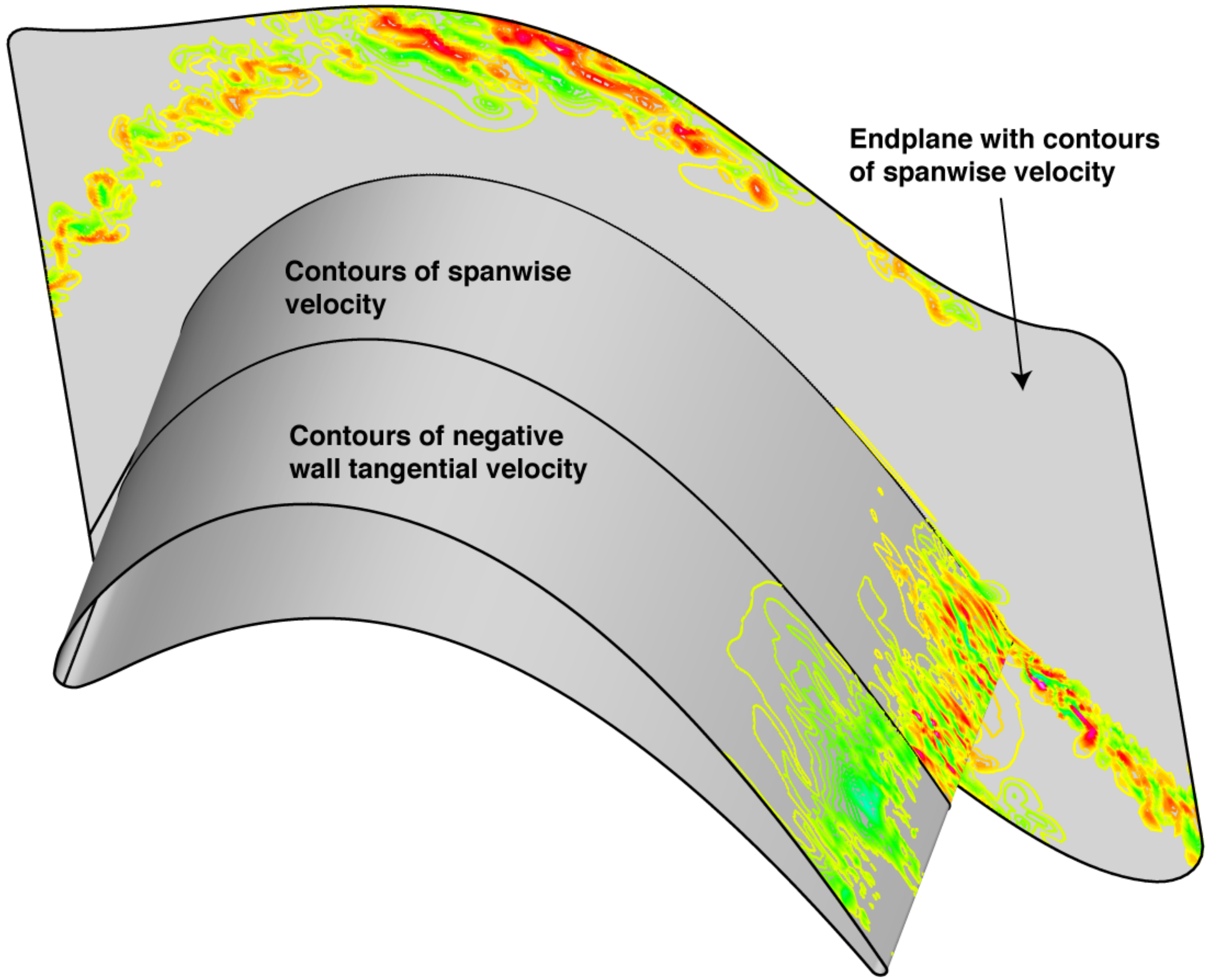
INSTANTANEOUS CONTOURS OF SPANWISE VELOCITY
(SIDE-VIEW, ϕ = 3.3)



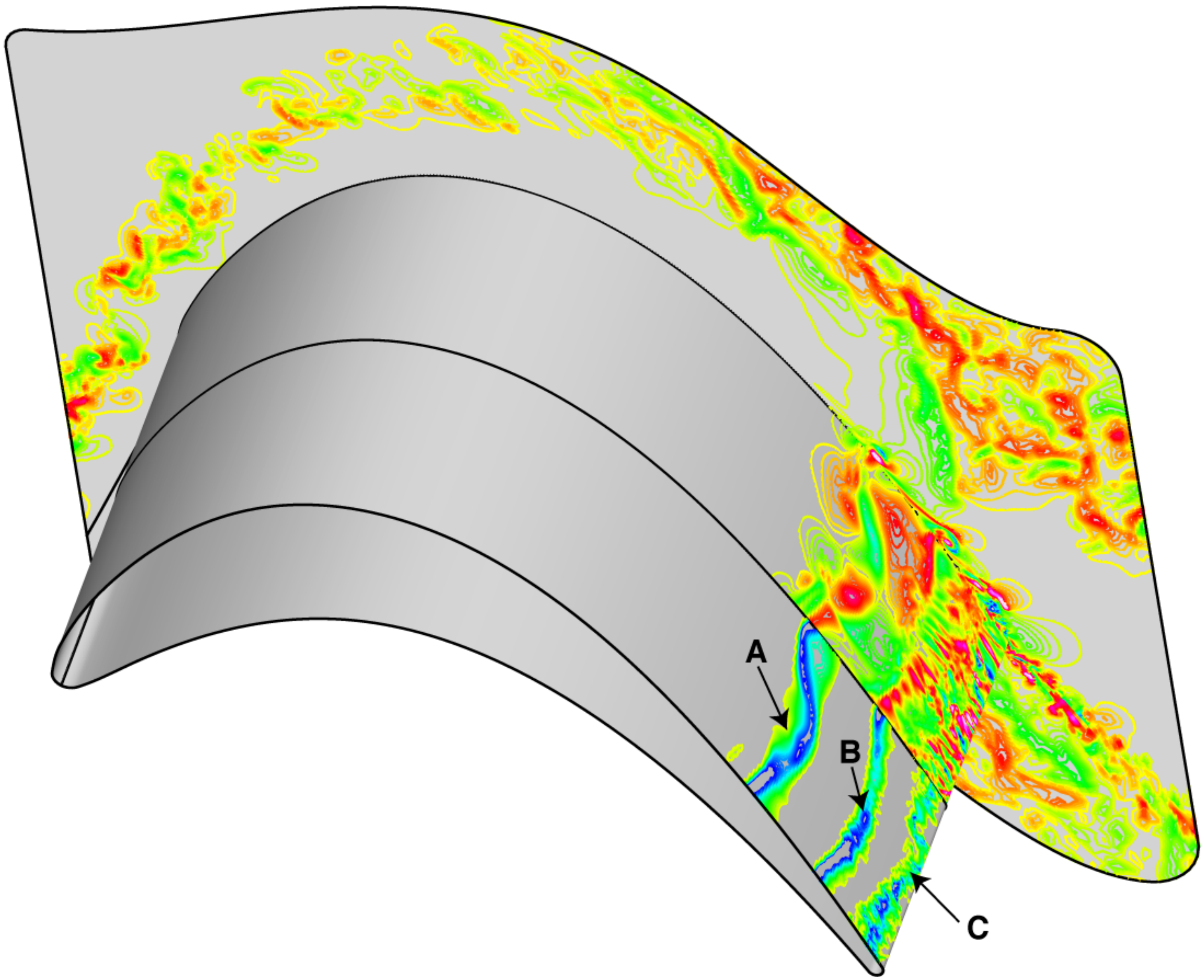
INSTANTANEOUS CONTOURS OF SPANWISE VELOCITY
(SIDE-VIEW, ϕ = 3.5)



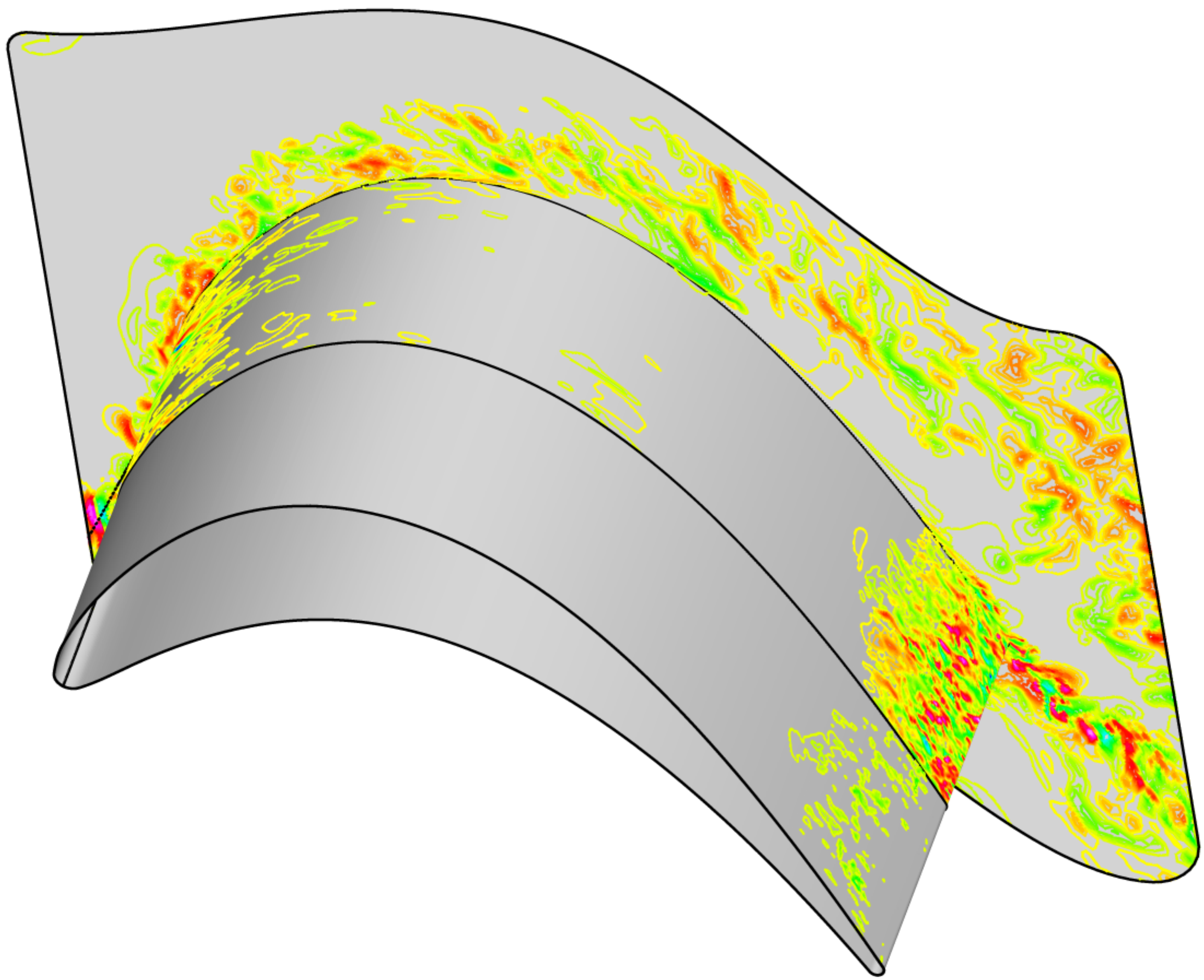
INSTANTANEOUS CONTOURS OF SPANWISE VELOCITY & NEGATIVE WALL-TANGENTIAL VELOCITY (ROTOR SUCTION SIDE, ϕ = 3.1)



INSTANTANEOUS CONTOURS OF SPANWISE VELOCITY & NEGATIVE WALL-TANGENTIAL VELOCITY (ROTOR SUCTION SIDE, ϕ = 3.3)



INSTANTANEOUS CONTOURS OF SPANWISE VELOCITY & NEGATIVE WALL-TANGENTIAL VELOCITY (ROTOR SUCTION SIDE, ϕ = 3.5)



UTILIZING DIRECT NUMERICAL SIMULATIONS OF TRANSITION AND TURBULENCE IN DESIGN OPTIMIZATION

Some Attributes Of DNS:

- **First principles approach to computing transition & turbulence (model free)**
- **Flow features computed in great detail**
- **Not practical as yet at high Reynolds numbers (compute intensive)**
- **Reynolds numbers in many turbomachines are modest (0.1 to 2 million)**

Uses for DNS data:

- **Provide designers physical understanding necessary for advanced designs and flow-control mechanisms**
- **Assessment of new designs**
- **Data for design optimization (response surfaces, search directions etc.)**
- **Physical understanding & data for turbulence modeling**

Objective of Present Investigation

- Reduce differences between expected and actual performance levels in CFD based aerodynamic design in situations where turbulence & transition modeling is problematic
- Explore the use of “DNS in the optimization loop”
    - Redesign LPT blade section to reduce total pressure losses
- Explore the use of DNS in design assessment
    - Assess surface heat transfer rates for baseline HPT stator airfoil section (UTRC) & airfoil designed using RANS with the potential of reducing heat transfer over a portion of the suction surface

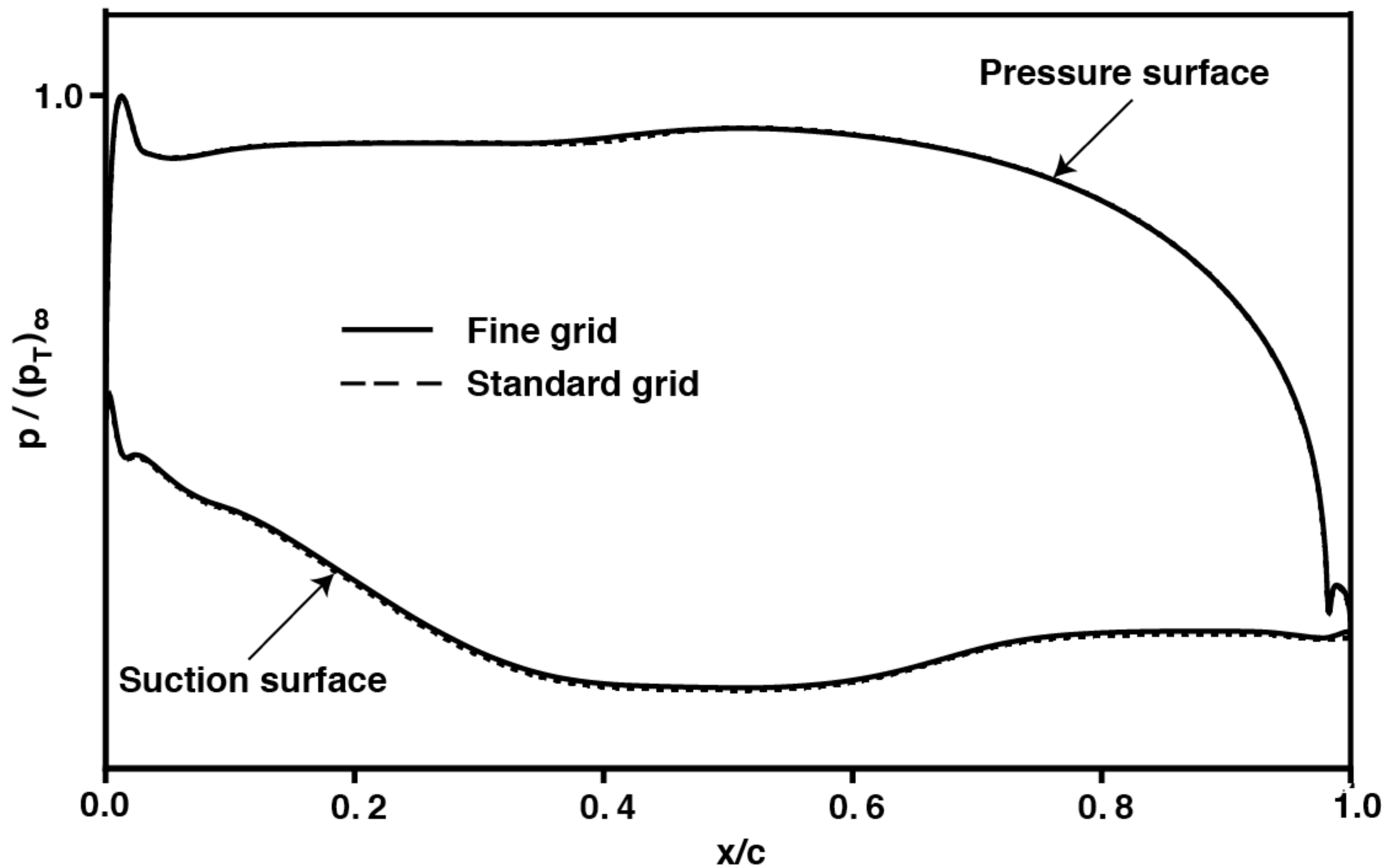
LOW PRESSURE TURBINE BLADE SECTION OPTIMIZATION

(PRESSURE SURFACE)

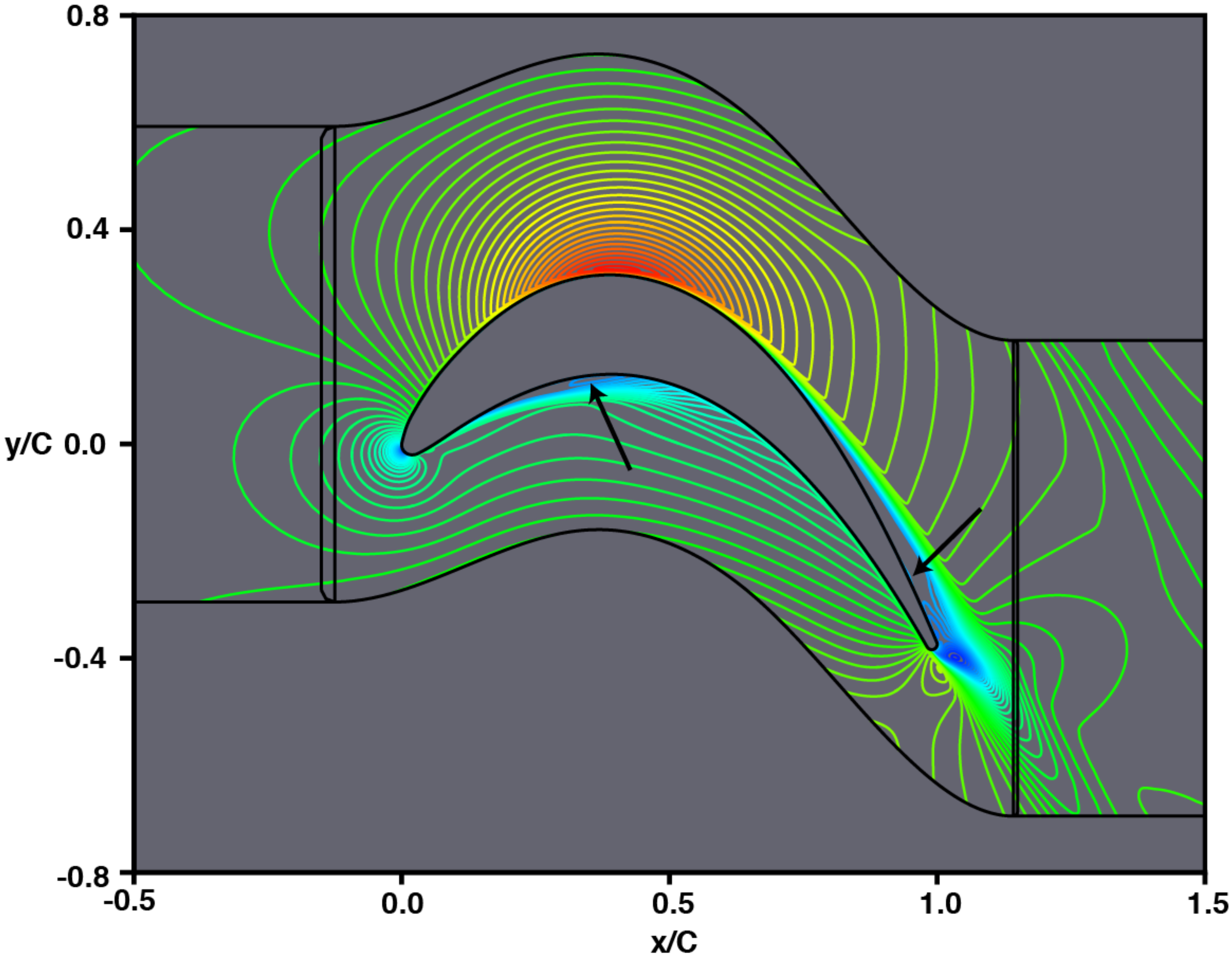
Objective/attributes of LPT blade section redesign

- Redesign LPT blade section to reduce total pressure losses
- Total pressure data from DNS used to construct response surface
- Optimal airfoil shape obtained via search of design space using response surface
- Both fine-grid (89 million grid points) and standard grid (16 million grid points) simulations used in redesign
- Response surface constructed with data from standard grid DNS
- Assessment of baseline and optimal airfoil sections performed with combination of standard and fine grid DNS

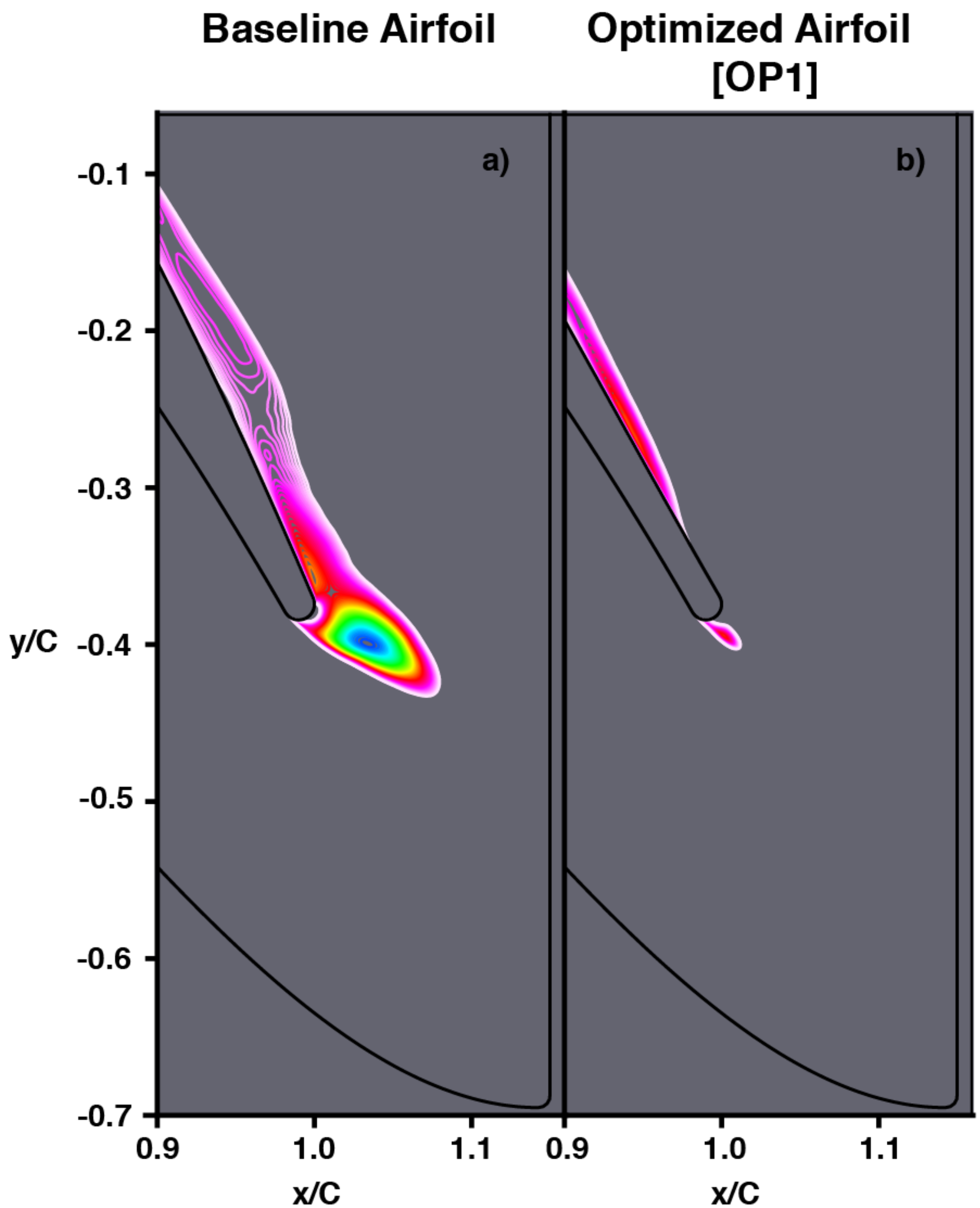
TIME-AVERAGED AIRFOIL SURFACE PRESSURE DISTRIBUTION
(BASELINE AIRFOIL)



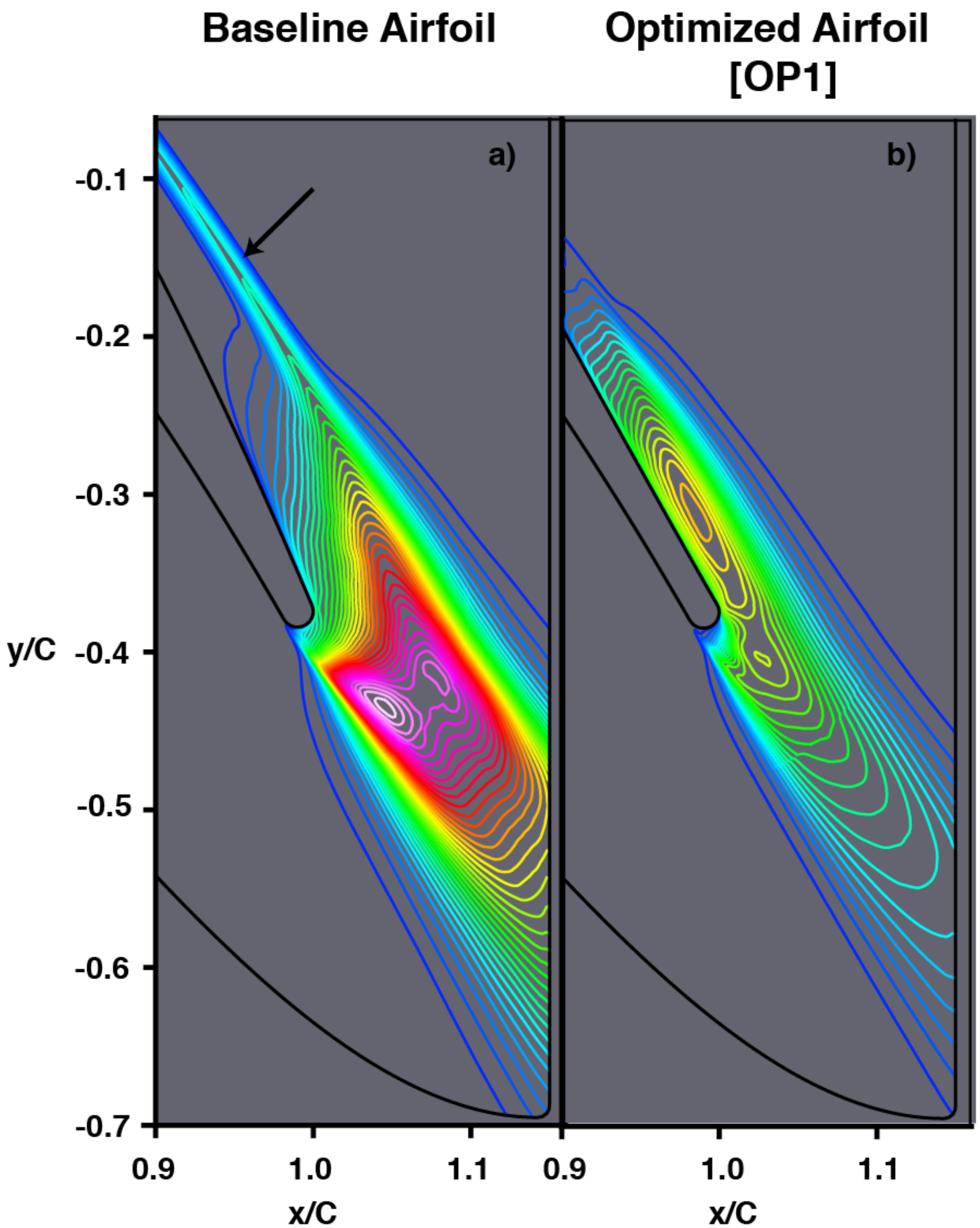
CONTOURS OF TIME-AVERAGED STREAMWISE VELOCITY
(BASELINE AIRFOIL)



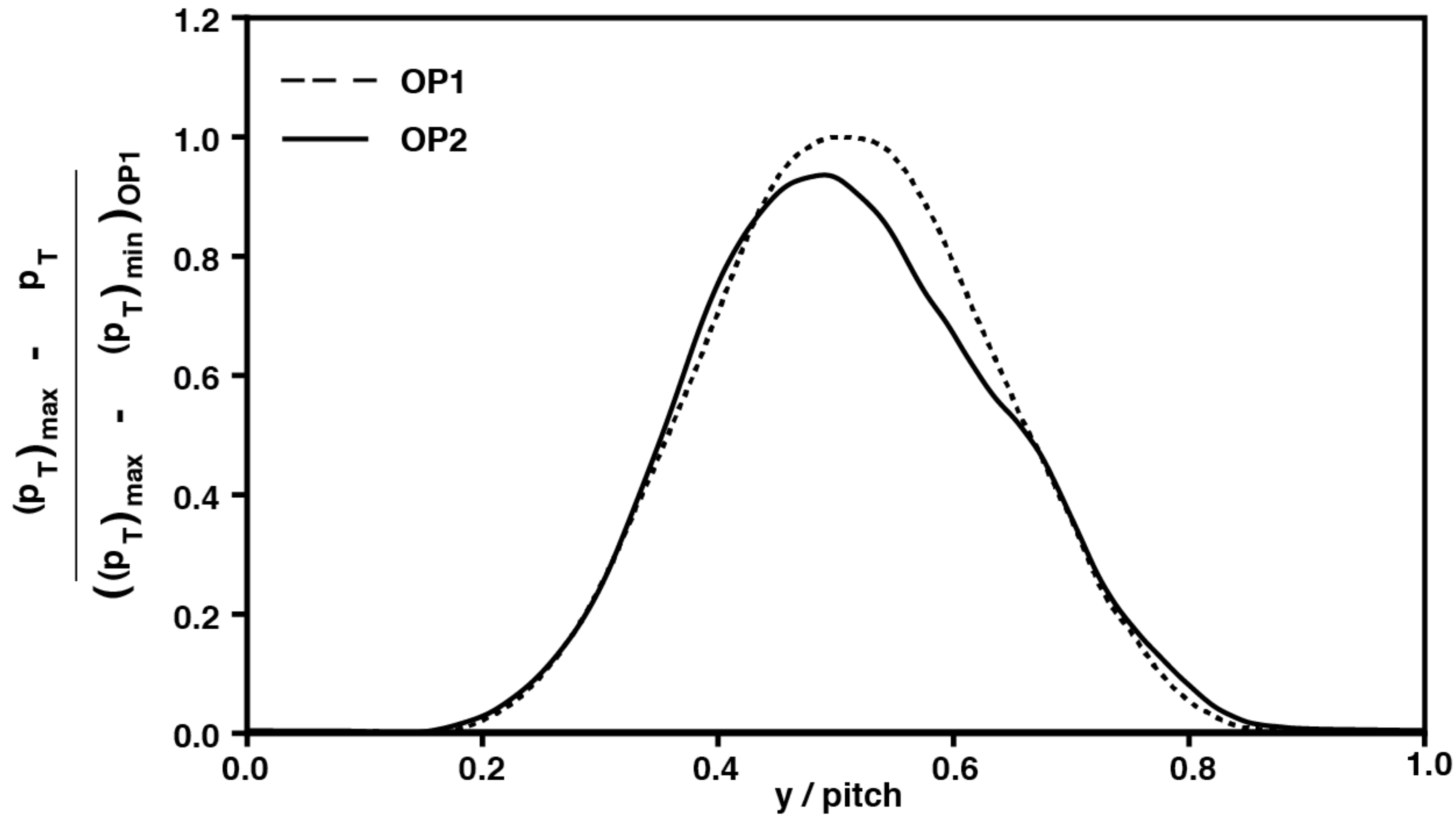
CONTOURS OF TIME-AVERAGED NEGATIVE STREAMWISE VELOCITY



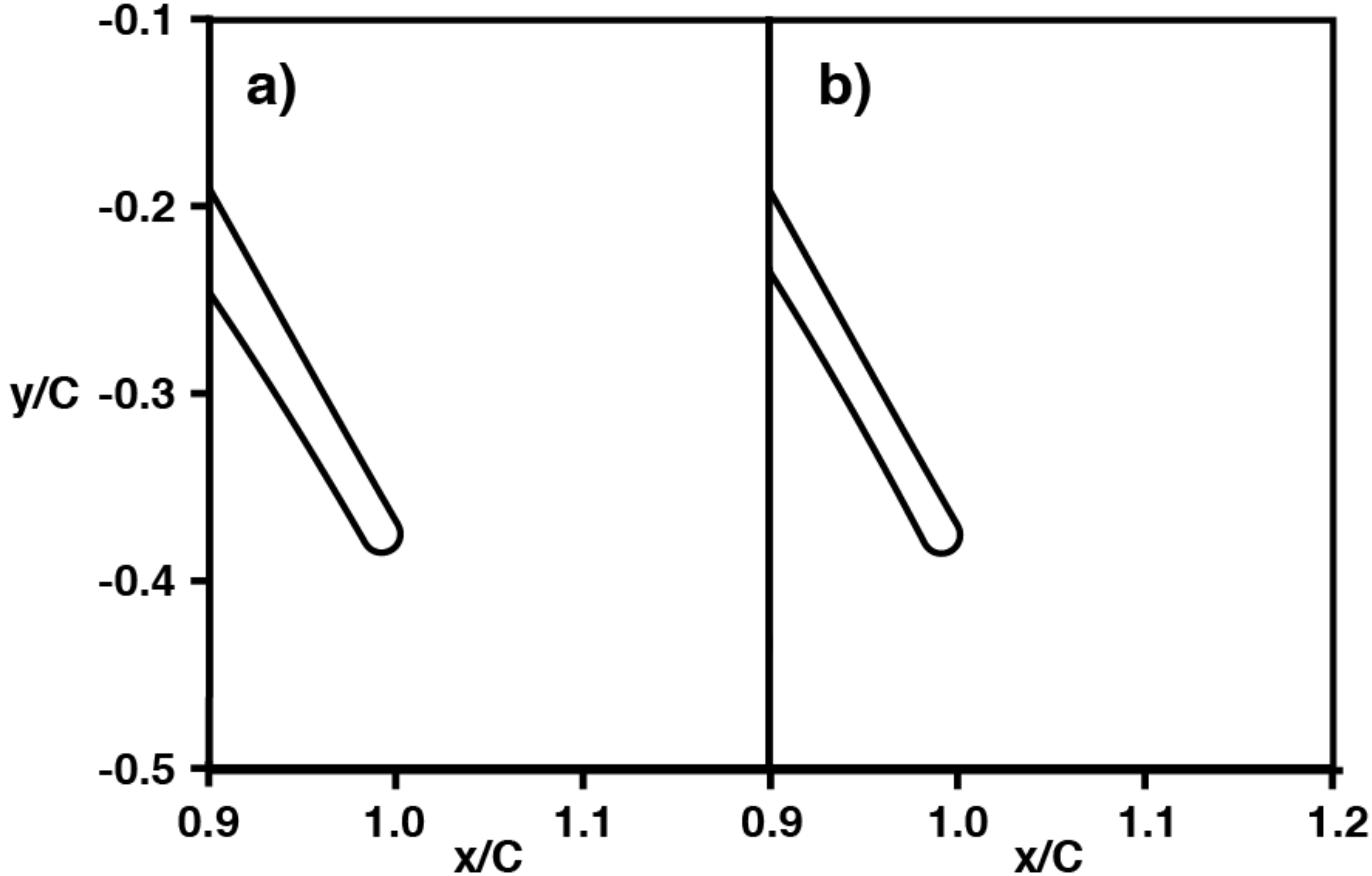
CONTOURS OF TIME-AVERAGED FLUCTUATING KINETIC ENERGY



Comparison of computed (DNS) total pressure loss profiles
at 0.5C downstream of trailing edge for OP1 & OP2 airfoils



Comparison of a) OP1 & b) OP2 airfoil geometry

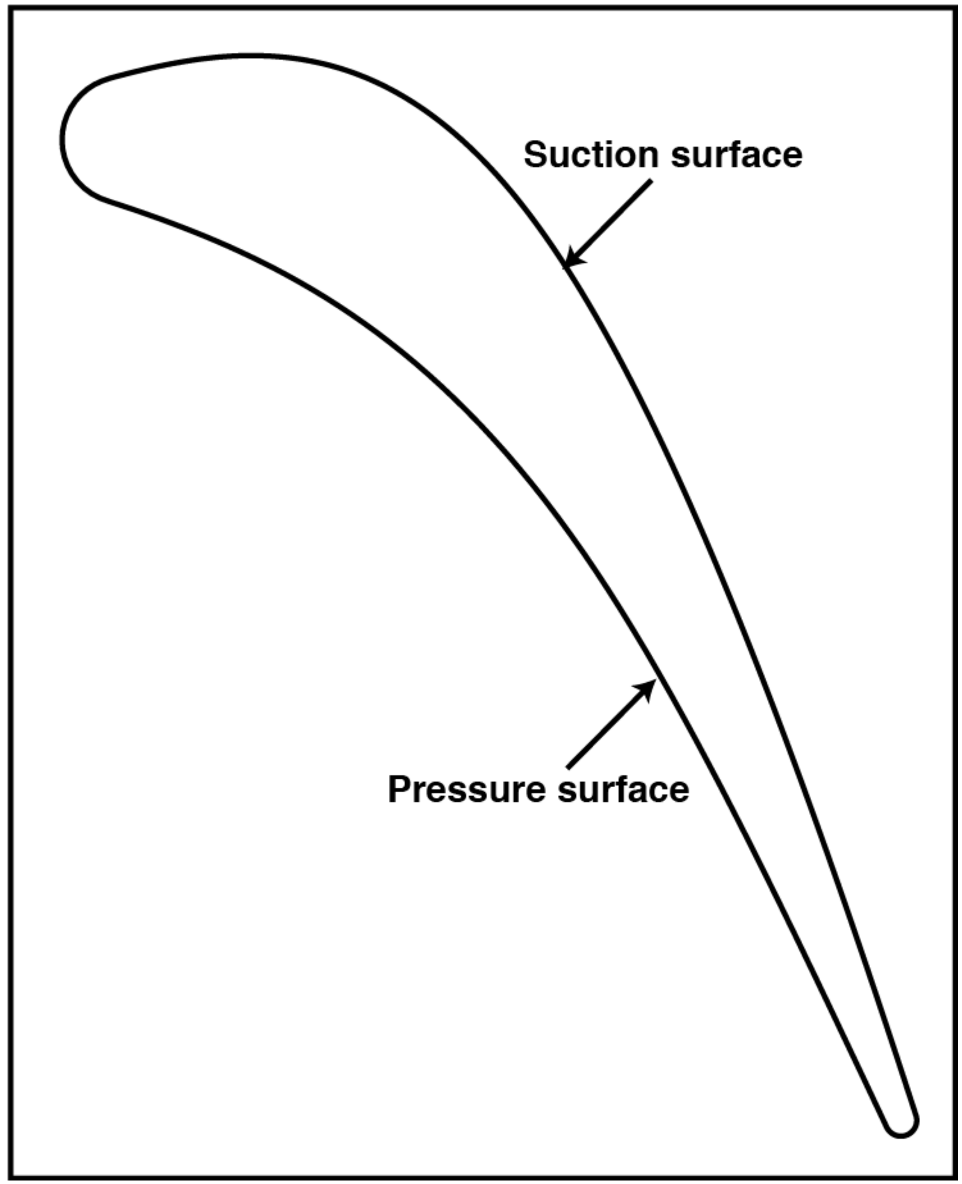


ASSESSMENT OF HIGH PRESSURE TURBINE STATOR SUCTION-SURFACE HEAT-TRANSFER RATE

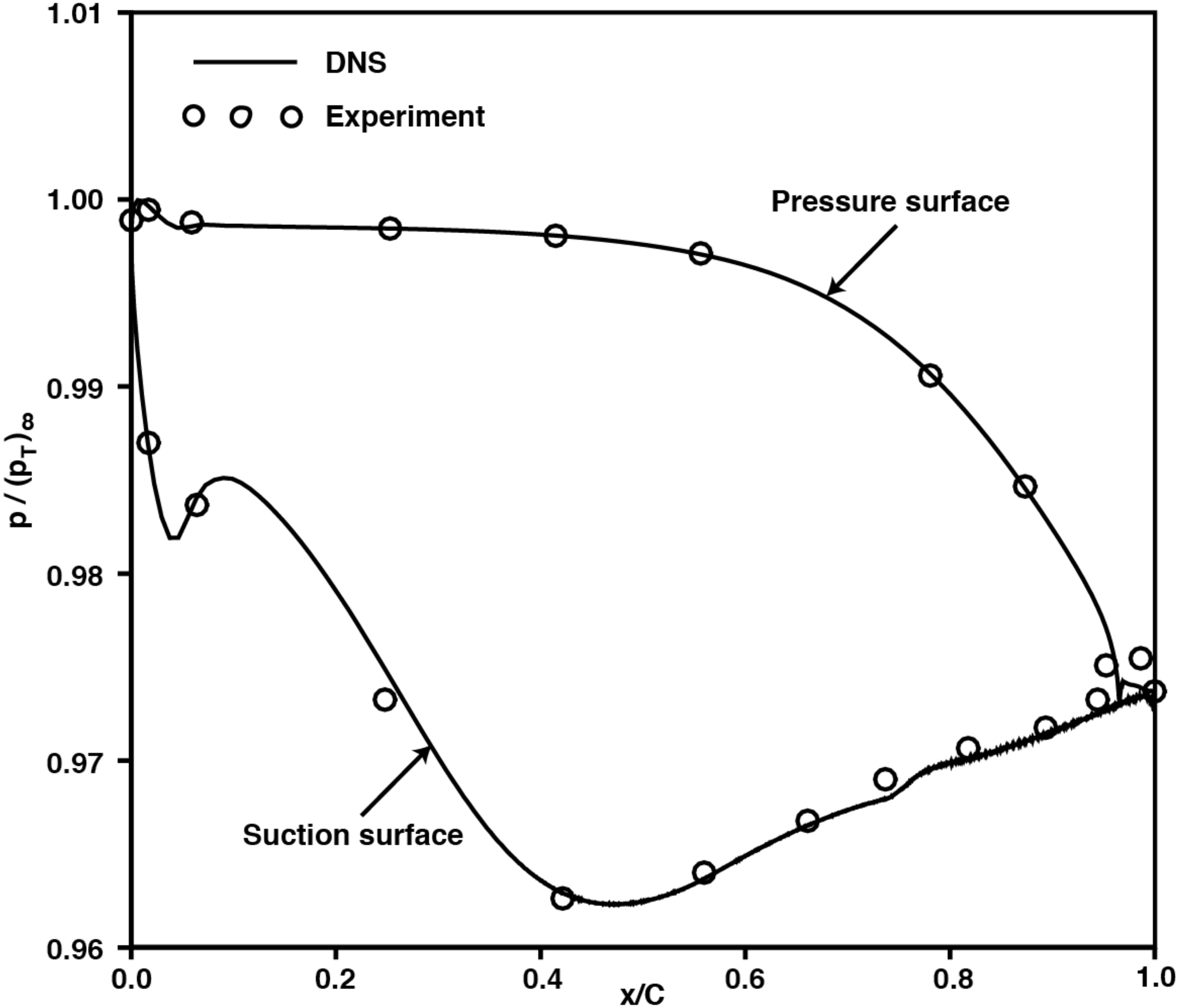
Tasks involved in surface-heat-transfer-assessment exercise (UTRC and proposed HPT stator)

- **Obtain HPT stator section with potentially reduced heat transfer rate on suction surface**
    - **Locate suction surface pressure minimum further downstream than obtained in the case of the UTRC stator airfoil**
    - **Use pressure data from RANS solver to construct response surface and search design space for required airfoil shape**
    - **New pressure distribution expected to delay flow transition**
    - **New airfoil referred to as delayed transition or DT stator**
- **DNS assessment performed for both UTRC & DT stators with approximately 57 million grid points**

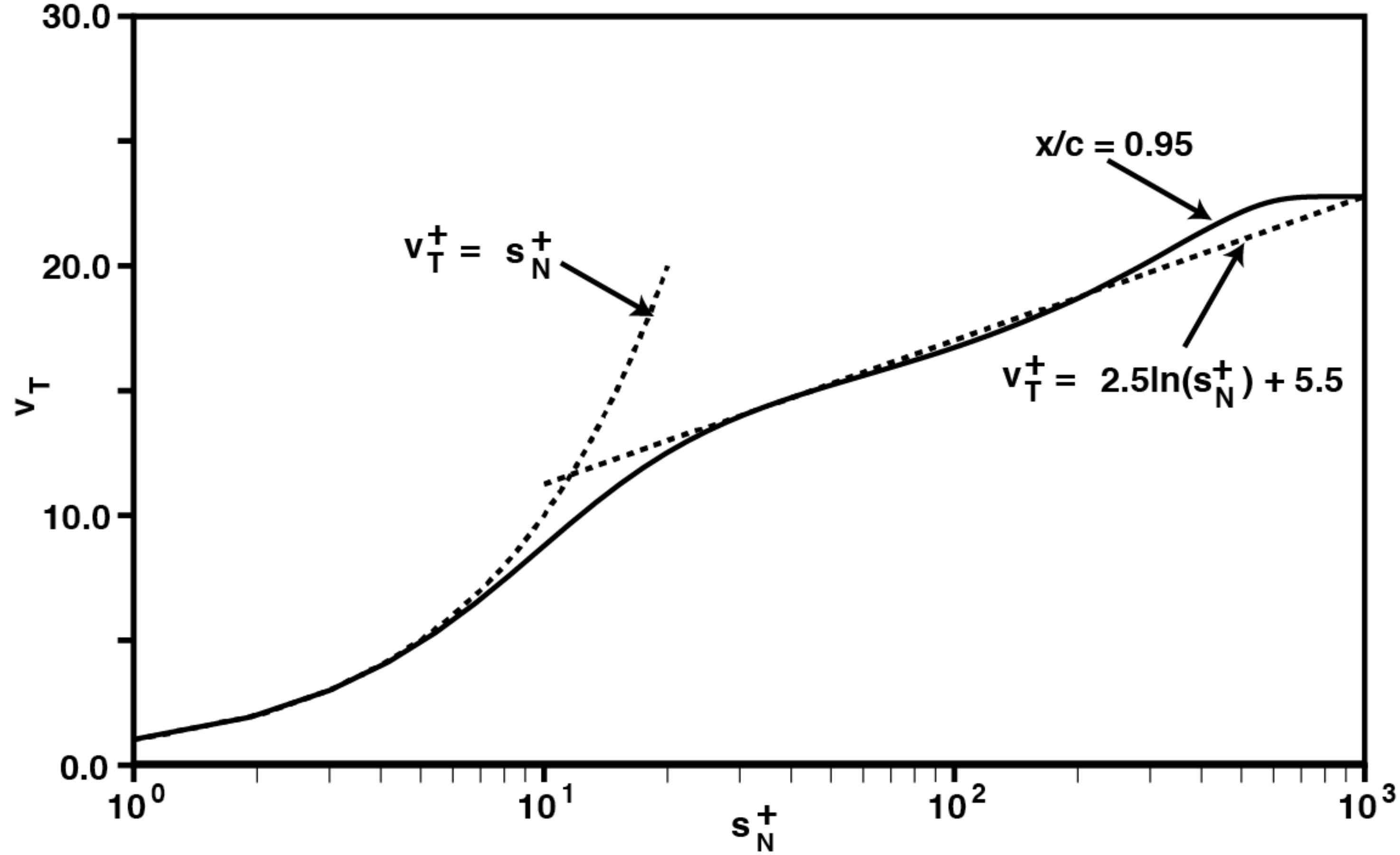
Midspan cross-section of UTRC airfoil
(Dring, Blair, Joslyn & Verdon)



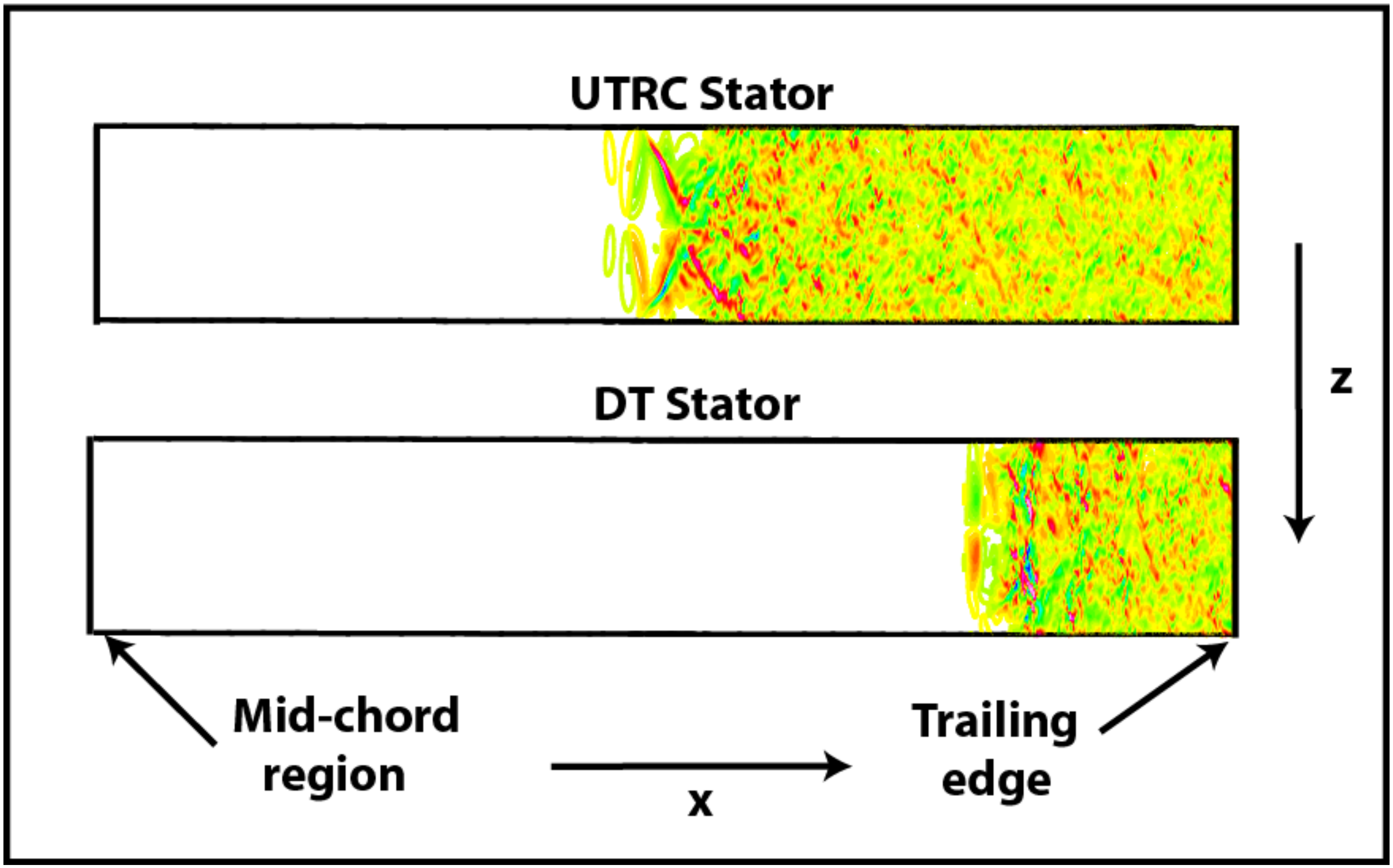
Comparison of computed (DNS) and experimental (UTRC) surface pressure distributions for UTRC airfoil



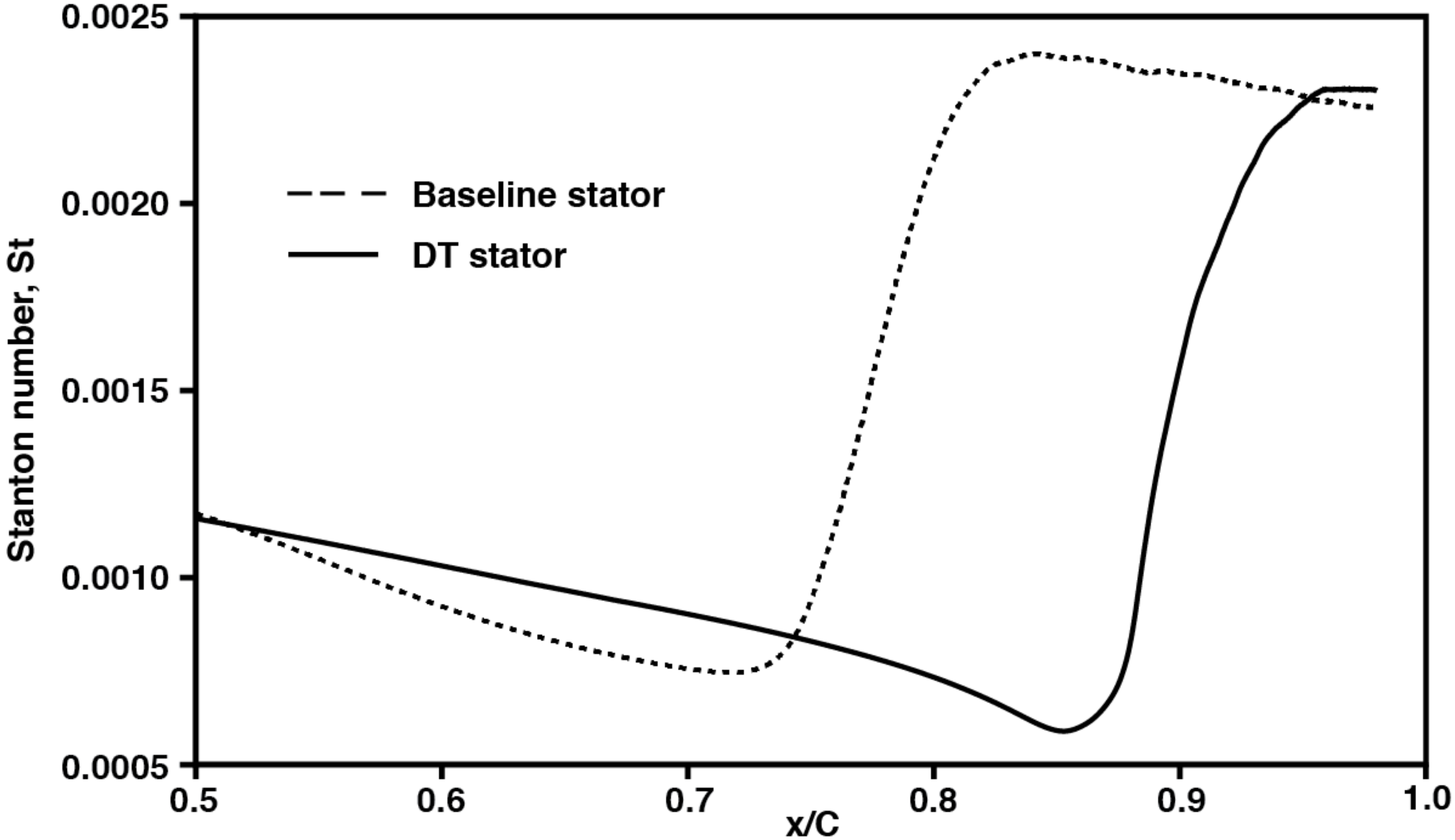
Time-averaged velocity profile (wall-tangential component)
at x/C = 0.95 on suction side of UTRC airfoil



Contours of instantaneous spanwise velocity on the UTRC and DT airfoils



Comparison of computed (DNS) suction-surface Stanton number distributions on the UTRC and DT stator airfoils



Concluding Remarks

- “DNS in the optimization loop” may be essential to obtaining advanced, next-generation designs in some cases
- Total pressure loss was reduced by approximately 4.9% in one optimization step in present LPT blade section (pressure surface) redesign
- Computing cost was appproximately 90,000 single-core hours (2.66GHz) for obtaining OP1….roughly half as much was used in obtaining OP2
- Surface heat transfer rate assessment for UTRC & DT stators performed with DNS
- Obtaining performance improvement over a range of operating conditions may result in a multi-objective optimization problem
- Designing a blade section that is relatively insensitive to changing operating conditions may require concepts such as robust design optimization
- DNS will play increasing role in design optimization